Development of Simulation-Based Genetic Algorithms Model for Crew Allocation in the Precast Industry

By

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DEDICATION

"This dissertation is dedicated to my parents who have motivated and encouraged me during all stages of my study, without which I could not continue this work”

DECLARATION

I hereby declare that this thesis is my own work and effort and that it has not been submitted anywhere for any award. Where other sources of information have been used, they have been acknowledged

Signature: ……………………………………….

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ABSTRACT

The focus of this thesis is on the precast concrete products manufacturing industry, which as one of the labour-intensive industries requires a substantial number of highly skilled operators in terms of crews to produce the final product. A crew is a group of multi-skilled chargehands and operators that have various skills and experience necessary to conduct an activity in a professional way.

The high cost of skilled operators and the apparent inefficiencies of utilising such skilled operators in the industry are the major driving force. To achieve this, optimal crew allocation is required. Crew allocation is complex because of the multi-criteria nature of the problem and availability of thousands of possibilities and allocation alternatives.

There is a gap in previous research efforts associated with crew allocation planning in the precast industry. Current practices suggest that the crew allocation process is carried out intuitively and the allocation of crews to production processes is subjective. This has led to high process-waiting times, improper allocation of skilled operators and ultimately higher production costs. In this context, the aim of this research is to propose an effective crew allocation methodology and a computer-based intelligent simulation model for its implementation. The objective of the approach is to guarantee a better workflow through minimising process-waiting time, optimising operator utilisation, and subsequently reducing the allocation cost.

This research develops a holistic and integrated methodology for modelling crew allocation problems by reviewing state-of-art resource allocation techniques, structured interviews with production managers, site visits and a detailed case study. The methodology is developed using an IDEF0 process model and a generic process map for both the business and the production processes of the precast manufacturing system. A multi-layered genetic algorithm model is developed in conjunction with a process-simulation model to form a hybrid allocation system dubbed 'SIM_Crew'. The model incorporates databases (Excel and MS Access), a simulation model (developed using

Arena 12.0) and genetic algorithms (developed using Visual Basic for Applications) to facilitate the generation and evaluation of various “what-if” crew allocation scenarios. A number of performance criteria have been developed to evaluate the allocation plans. ‘SIM_Crew’ enables the investigation and analysis of allocating possible schedules and provides a facility to visualise the production processes. ‘SIM_Crew’ was validated using real life case study data and it was concluded that the allocation of crews to precast processes using genetic algorithm improves the throughput time and reduces the allocation cost as compared with real life production data. It is anticipated that future use of this research will solve the crew allocation problem in the precast industry.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The precast concrete industry is comprised of manufacturers of precast concrete products and produces over 35 million tonnes of products every year, is worth an estimated £2 billion and employs in excess of 20,000 people, Goodier (2006).

The precast manufacturing system is undertaken in a specially-equipped factory, under controlled conditions, and undergoes routine quality control inspections. In addition, the precast production operation consists of a mixture of labour and machine operations. This mixture led this industry to be considered as a labour intensive industry.

In the precast labour-intensive industry, each manufacturing system involves a number of specialised labour-driven processes. A number of multi-skilled operators are required to operate physical resources in order to carry out jobs in such processes. The cost of hiring such skilled operators is high and can be considered as a substantial factor that can influence in saving both production cost and time.

The increasing cost of skilled labour is a major force that drives production managers in the precast industry to improve productivity and hence minimise the total production cost. To improve productivity in such a labour-driven production facility, optimal allocation of resources and planning/assignment of the workforce are crucial. Optimal allocation of workforce will eventually lead to minimisation of waste (cost and time) and guarantee a good flow of work. In case of full workforce employment does not exist, partial assignment of multi-skilled workforce is most useful, Gomar et al (2002).

The process of planning and allocating each team of workers (known as a crew) to be assigned to the right process is very important. This allocation process is a complex combinatorial problem; and the "classical problem solving" techniques cannot be used to obtain satisfactory results (Onwubolu 2002). More sophisticated tools are required acting as decision support systems.

Developing advanced systems to solve crew allocation problems in such labour-intensive manufacturing systems motivated this research to develop and test an innovative crew allocation system that could assist the production planner in identifying the best allocation plan of his/her labour-driven production facility, in order to improve performance and efficiency of the facility. The optimal allocation of crews of workers to processes will minimise associated labour costs, optimise labourer utilisation, reduce process-idle time and subsequently improve productivity.

1.2 BACKGROUND OF THE PRECAST LABOUR-INTENSIVE INDUSTRY

Labour-intensive industry describes an industry or sector of the economy that relies heavily on the input of labour, or in other words the extensive employment of human capital or skilled labour compared with other industries or sectors. As the name implies, such industries 'use labour intensively'. The term "labour intensive" can be used when describing the amount of work that is assigned to each worker/employee, emphasising on the skills required to carry out such work in a production facility.

In order to process or carry out works on such processes, workers need to be allocated as individual workers or as a group of workers on the desired processes. A group of workers or a "crew"; requires the operators within the team to have enough skills, experience and abilities to carry out the allocated work in a professional manner.

Skill levels might vary from one worker to another depending on the worker's qualifications, experience and proficiency. In the precast industry, labour costs, which are considered as a measure of the economic value of an employee's skill set, increase due to the shortage of highly skilled labourers.

The cost of hiring a worker in the precast manufacturing environment depends on his/her skill level and his/her number of working hours. Involving a team member in more than one process depends on his/her skills. As a result of accumulated experience, multi-skills can be obtained by the training and involvement of team members in more than one process. Teams containing trainees can be expected to perform at lower levels of efficiency until skill levels are improved. (Goodier 2006)

The progression of work in the precast industry depends on having the required skill and an efficient workforce planning system. This industry has advantages in controlling expenses during market downturns by controlling the size of the employee base using an appropriate labour planning system known as "manpower planning".

1.3 THE PRODUCTION PROCESS IN THE PRECAST CONCRETE INDUSTRY

In this section, the precast production process and role of skilled workers during this process is explained in detail. Labour-driven processes in a precast manufacturing system was described by (Leu and Hwang, 2002) when they decomposed the precast production operations into seven activities: reinforcement cage prefabrication, mould fabrication, mosaic or tiling fixing, reinforcement cage instalment, placing concrete, steam curing, and cleaning and finishing, see figure 1.1

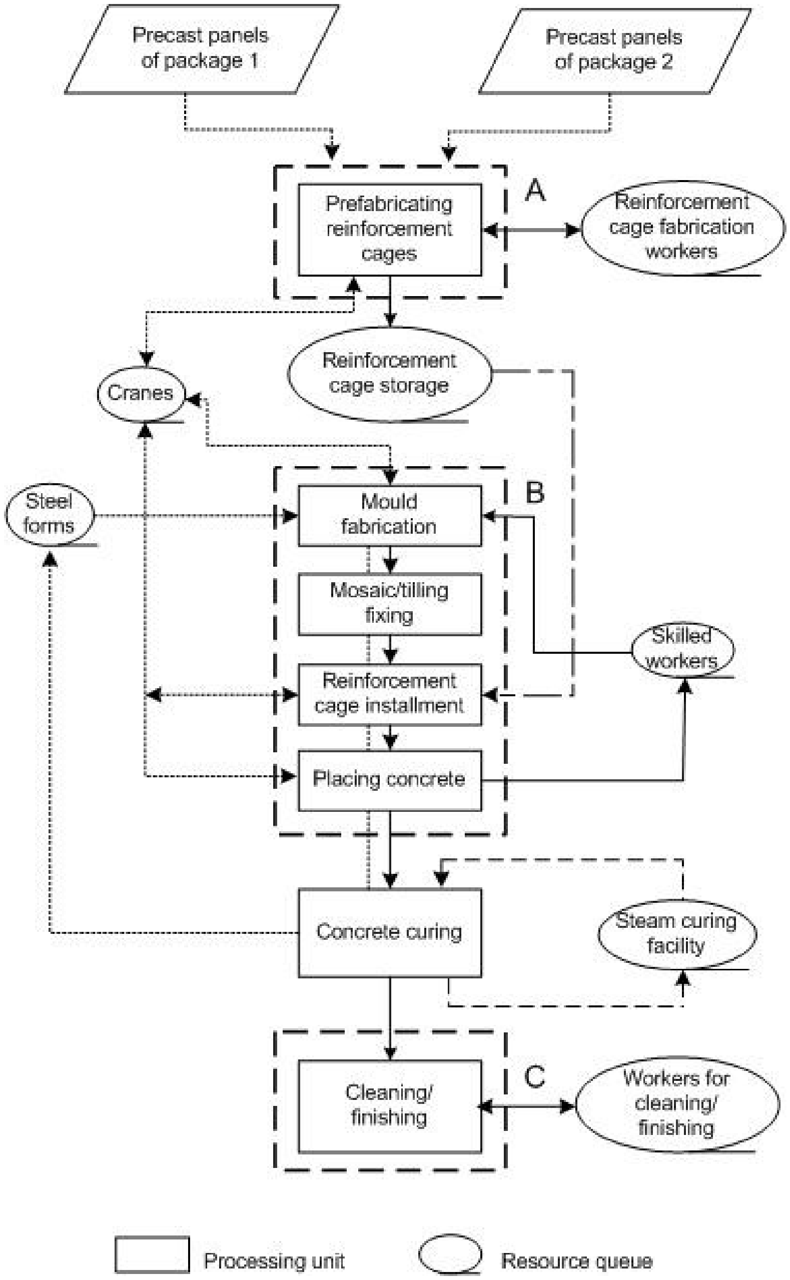


Figure 1.1: Mixed-production precast production process (Leu and Hwang, 2002)

In order to identify the role of skilled workers in each process, the precast operation was further re-organised into three zones A, B and C: In Zone A, reinforcement cage prefabrication activity starts by allocating a specialised crew of workers to reinforcement cage fabrication activity. Zone B covers the activities of mould fabrication, mosaic or tiling fixing, reinforcement cage instalment and placing concrete and it can be regarded as the kernel of the repetitive precast production process. Activities in zone B require more than one crew of workers; each crew is responsible to carry out an individual activity.

The concrete items being poured need to wait in a steam or warm curing space, the steam curing process generally starts after concrete pouring completion. In Zone C, activity of cleaning and finishing operations is involved, cleaning/finishing crews are allocated to clean and finalise the cured products.

1.4 THE ROLE OF THE PRECAST PRODUCTION SYSTEM LAYOUT ON THE RESOURCE ALLOCATION PROCESS

Each production system in the precast concrete industry has a typical layout. The production system layout is the spatial arrangement of physical resources used to produce the final product (Lussier 2008). This layout depends on the arrangement of a facility such that resources can be used to make similar products or families of products in a group called a “cell”. Many production systems have multiple production lines; each production line might produce similar/different products. Because of the high cost of some physical productive resources, shared resources can be a good alternative.

A number of precast manufacturing system layouts involve repetitive labour-driven production processes, in which skilled labourers and experienced supervisors are essential to carry out the required job in more than one similar/different operation activity. Labour-driven production processes are those processes that require multi-skilled workers to carry out the work activities. These types of processes are usually associated with a job-shop production environment as seen in a precast manufacturing system (Halpin and Riggs 1992). Other types of production system layouts can be seen in *Appendix B*.

Production processes involved in a number of labour-intensive manufacturing systems are repetitive, i.e. "have similar processes along the production line", the correct management of labour is a key factor in improving the productivity of such production systems. The planning and management process of crews of workers is a complex process especially when each crew member requires one or more skills to perform a job, each crew member has different skills according to the requirements of the process itself, and each crew has a different formation (Gomar et al 2002). The process is more complex when each process has a set of crew alternatives; each alternative might have shared workers with the capability to do the current job in a certain process time.

"Parallel-Repetitive" production system layouts exist in job-shop environments such as the precast concrete industry. In this layout, all production processes have a similar sequence, and the same materials are processed by similar parallel repetitive processes in order to produce same or different products in a short cycle time. Figure 1.2 for parallel-repetitive processes.

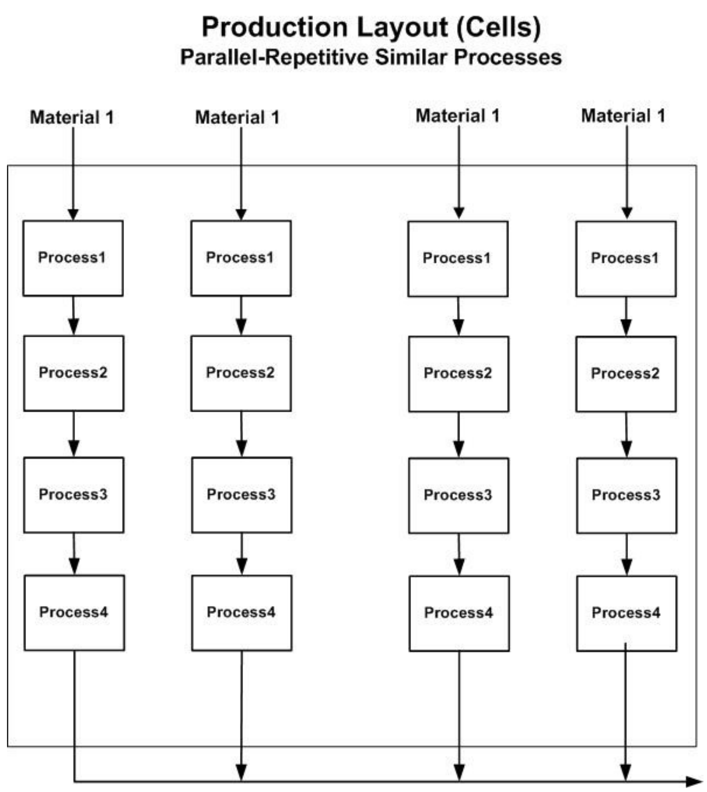


Figure 1.2: Depicts parallel-repetitive similar processes production system layout

All inputs of such production system are the same; inputs for any production line are processed through the same sequence of processes. In this production layout, each line has a shared resource (for example a common mixing plant in the case of the precast concrete industry) especially where physical resources are too expensive to be assigned to an individual line. These shared resources can alternately be assigned (by using pushers, conveyors, and other transporters) to carry out jobs of two successive lines.

Sharing a resource can be a bottleneck, since a number of 'competing' or dependant processes share a single resource (Leu and Hwang 2001). Appropriate scheduling of shared resources is required to reduce process-waiting time and to increase productivity.

1.5 LABOUR ALLOCATION PROCESS IN THE PRECAST INDUSTRY

Labour allocation is the process of identifying the right number of workers with the right skills and experience to carry out the right job at the right time in order to satisfy requirements of any labour-intensive production system. These requirements include: a guarantee of the best flow of work, best allocation of resources, minimum allocation costs etc (Elhag et al 2005). In the precast industry, an effective workforce plan is an essential to identify appropriate workload staffing level and justify budget allocations so that the precast industry can satisfy its requirements. In order to satisfy the precast production process objectives, a range of goals have to be considered in order to deliver objectives such as: optimising labour utilisation, reducing process-waiting times, and diminishing bottlenecks that might cause any work delay.

1.5.1 Benefits of Labour Allocation Process in the Precast Industry

The labour allocation process is used to enable precasters to identify a suitable labour allocation plan in which a better workflow and better performance can be obtained. The benefits from using a labour allocation process are as follows:

- Reduce labour costs rapidly without negatively impacting productivity.
- Increase the overall productivity of the workforce.
- Identification and preparation of future leaders and managers for future opportunities.
- Maintain a flexible workforce.
- Proactively move skilled and semi-skilled workers internally to maximise the productivity returns from them.
- Consistency in workforce functionality leading to more effective working.
- Forecasting labour allocation plans.
- Create workforce innovation management.

The above benefits vary from one industry to another; the nature of variation depends on the type of product or production layout design etc.

1.6 RESEARCH PROBLEM: LABOUR ALLOCATION IN THE PRECAST INDUSTRY

In the precast manufacturing system, a system of crew allocation is required to decide when and where each crew member should be allocated according to the skills and qualifications required for completing a given process. Each crew has a collection of workers; each worker, depending on his/her skills is able to accomplish the required job at a different level of productivity or process time. The skills required to carry out a process must be possessed by the members of the crew that are allocated to conduct that process.

A crew allocation problem appears when the formation of any crew involves shared workers working on simultaneous similar/different processes. This type of labour sharing can cause process-waiting times, labourer idle times, low resources' utilisations, a disturbed work flow and subsequently high allocation costs. Since a parallel or sequential similar/different processes structure of a manufacturing system is pre-specified, the involvement of shared workers can be required in one or more processes.

This type of problem becomes more important when there is a significant allocation cost. This is caused by shared workers being allocated to more than one process and being required at same/different times, dictated by the sequence requirements of similar labour-intensive operations. In order to optimise resource utilisation and minimise labour allocation cost, an optimal/near optimal crew allocation plan is required in any labour-intensive facility. An appropriate crew allocation plan, which has to be selected between other plans, satisfies minimum allocation cost. Each production process has a minimum requirement for labourers and the satisfaction of such requirement can ensure the processing of jobs within production processes. The labour requirement of each process can be presented by a number of crew alternatives. Each process has a certain pool of crew alternatives that can possibly perform the workload in each of the parallel activities. These crew alternatives have different formations with a certain process time in which a different number of chargehands and operators are involved in each formation. The sharing of available labourers in different crews can potentially cause delays.

Parallel-Repetitive Similar Processing is a realistic example of a resource sharing case. All production processes in such a layout have a similar sequence and similar parallel repetitive processes, in order to produce the same or different products in a short cycle time, to process the same materials. This type of production layout can be seen in a job-shop environment existing in the precast concrete industry, see figure 1.3 for a diagram of the crew allocation problem.

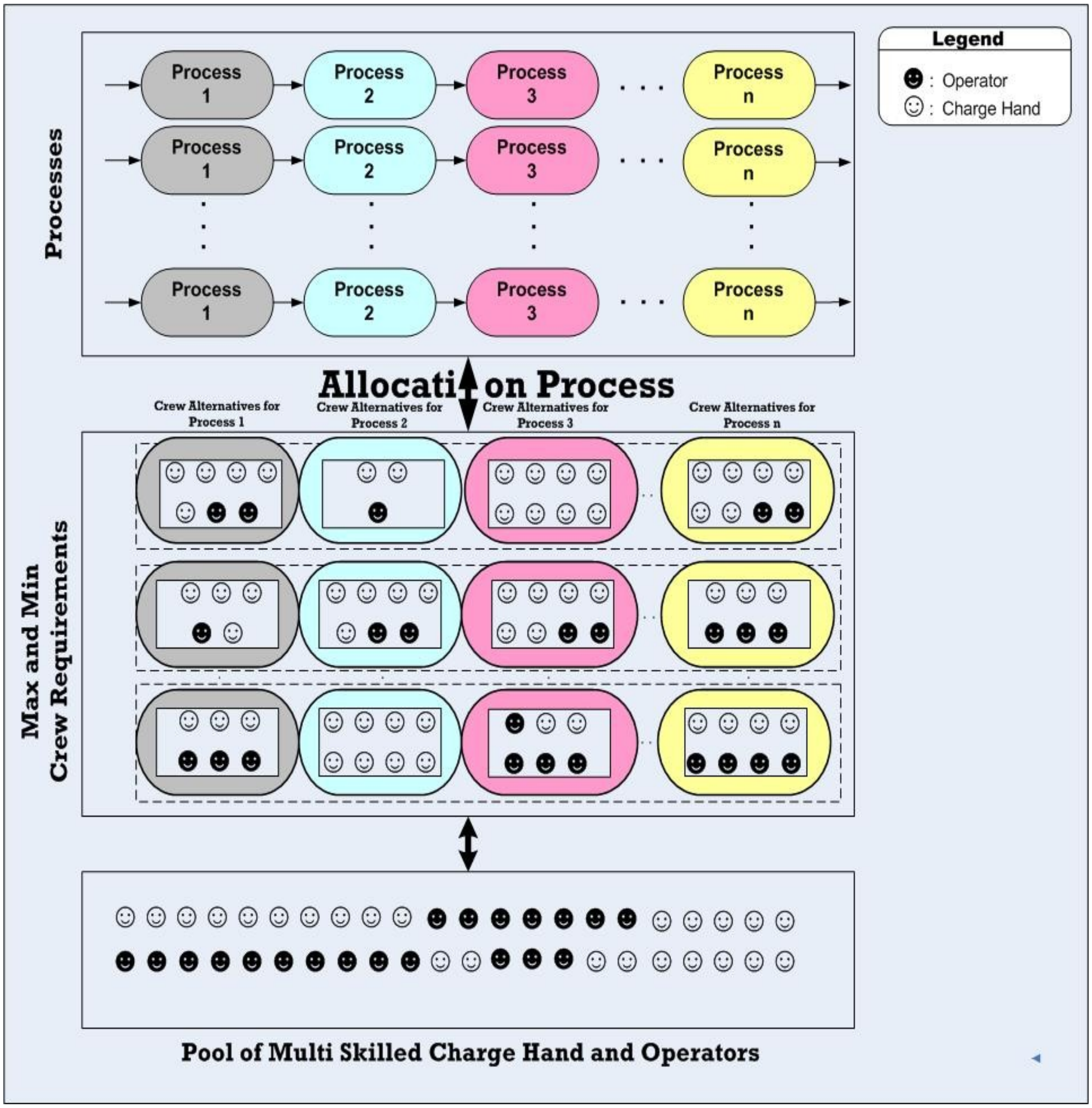


Figure 1.3: Schematic diagram for the crew allocation problem in the precast industry

In figure 1.3, the allocation process for a particular process starts with identifying the minimum requirement of the required labourers (different skilled workers). A number of crew alternatives are available for the process that can satisfy the minimum labour requirement and also provide more than the required output, in terms of providing different types and larger numbers of skilled workers. After selecting the crew of workers, the crew formation (crew members) is recalled from the workers pool. Delays occur, when the worker being utilised is required for more than process at the same time, in which the status of the utilised worker in the workers pool is addressed as an 'engaged' worker. The 'idle' status of the worker can be obtained after releasing him/her from the assigned job back into the pool and hence the worker can be re-allocated to other processes.

In order to identify the optimal crew allocation plan in the precast labour-driven processes with minimum allocation cost, a superior search mechanism is required to investigate possible allocation plans and identify the most promising solution. During the investigation process, an objective function is needed to decide the best outcome of allocation plans.

1.7 AIM AND OBJECTIVE OF THE THESIS

The aim of this research is to model various multi-skilled operators in the precast industry in order to solve the problem of 'multi-allocation' to labour-driven processes in such industry. In order to deliver the aim of the research, the following objectives have been established:

- To review the state-of-the-art knowledge in crew allocation used to date to model and solve complex crew allocation problems.
- To develop specification and process mapping models for precast labour-intensive manufacturing system.
- To collect data as direct inputs of the simulation model.
- To develop a simulation model to imitate labour-driven production operations in the precast industry.
- To develop a 2D and 3D visualisation aspects of the developed simulation model.

- To develop an optimisation module based on an evolution concept. The searching engine is designed to be embedded in the developed labour-intensive simulation model.
- To verify and validate the logic and the efficiency of the proposed allocation system respectively.
- To compare the performance of the proposed model with other searching rules in order to identify whether or not the proposed model in comparison with other searching rules is performing better in terms of solution optimality and efficiency.

1.8 THESIS APPROACH/ METHODOLOGY

A combination of techniques and tools are employed depending on the basis of their suitability to capture various aspects of the system under investigation:

- Literature review of current theories and practices in simulation modelling and simulation optimisation. A comprehensive literature survey was conducted to identify the 'state-of-the art' to solve such complex allocation problems.
- IDEF0 was one of the visual modelling techniques used to map production processes. This mapping technique was useful in capturing the hierarchal structure of the industry and to understand the processes flow.
- A number of structured interviews were conducted in order to elicit data, and information from experts regarding the crew allocation problem in the manufacturing system being investigated.
- Discrete-event simulation modelling was used to translate the static model yielded by using the IDEF0 concept into a dynamic simulation model.
- 2D modules available in the ARENA Rockwell simulation package library were used to create the 2D animation. 3D Arena Rockwell is used to develop the 3D animation model.

- Genetic Algorithms (GA) were selected to be the optimisation module. GA optimisation was tailored to solve the production issues. The proposed module was developed to be coupled with the simulation model for improved searching capability.

- A case study of precast concrete labour-intensive industry was developed to prove the developed allocation system.

- Monte-Carlo sampling techniques (MC) and Simulated Annealing (SA) as one of the popular meta-heuristic methodologies were selected to be compared, with the proposed allocation system to determine its' effectiveness.

1.9 SCOPE OF THE THESIS

The scope of this study is limited to the resource allocation process, especially the crew allocation problem in labour-driven operations in precast manufacturing systems. A set of possible 'crews of workers' for each production process was identified and collected from one of the precast manufacturers in the UK. Suitable workers with the required skills were included in each crew. The process time for each crew of workers was retrieved from the workforce planning database in the case study organisation.

Consideration of the workers in simulation models was described as being useful for systems with a high rate of manual operations (Freudenberg and Herper, 1998). Hence, simulation software namely "ARENA" from Rockwell Automation was used to develop a simulation model that could be used to imitate the production operation in the precast labour-intensive industry. Optimising the selection process for crew allocation plans was enabled by developing a Genetic Algorithm model as a promising evolutionary solution algorithm.

1.10 SIGNIFICANCE OF THE THESIS

There are a number of significant points in this thesis:

- The designed process maps provided a holistic view on how precast concrete labour-driven manufacturing systems work, and identified the relationships between all production processes. How the workers could be allocated to carry out tasks each according to his/her skill.

- The developed simulation model for such production system was used to run different managerial scenarios regarding number of resources used, layout management, etc in order to improve performance of the concrete sleeper manufacturing system used as the case study.

- The proposed innovative crew allocation system 'SIM_Crew' can be applied in planning and allocation of crew's to production processes. This allocation system can be additionally used to suggest and decide on the best set of a predefined collection of possible resources "machines, operators, or both" to be allocated to a process amongst a large range of possible and available resource sets.

1.11 THESIS ASSUMPTIONS

Assumptions were necessary to prove the proposed concept of the developed crew allocation system, some examples of these are:

- A manufacturing systems-based job shop environment was considered as representing the precast labour-intensive industry.
- All crew members were assumed to be available. No random factor was considered while producing allocation plans.
- None of the environmental impact factors such as weather was considered to affect the workflow. (Note: only extreme weather condition affected the workforce in reality)

Therefore, in this study, the chosen manufacturing systems are considered as working in a closed environment.

- The crew members were assumed to be available when needed. No absence or other labour failure was considered in this study.
- An ideal status of resources was assumed in the study.
- The production planner provided a skills matrix of each alternative.
- Incomplete crew formation while working is considered as process-waiting time. The time that a process spends waiting for a complete crew formation, to carry out tasks, is a process-waiting time in the developed PROCESS TEMPLATE module.
- The entire manufacturing system consists of several manufacturing sections; each of them may have more than a production line.
- An average resource utilisation for both multi-skilled chargehands and operators was considered in this study.
- Any unemployed operative in a precast production section can be involved in carry out tasks in another production section.
- Multi-skilled operators are considered as able to carry out more than one task.
- The same individual cannot carry out more than one task at the same time. Delay time being available to enable the process of assigning a labour on more than a process at different period.
- Multi-shift working was considered in this study.
- Parallel and repetitive processes layout was considered in this study.

1.12 THESIS ORGANISATION

This thesis presents the research completed in three main topic areas: review and identification of crew allocation modelling approaches, development of crew planning and simulation methodology and design of a prototype model to reveal the benefits of the proposed allocation system. The current chapter includes the general background of the precast concrete labour-intensive manufacturing systems, types of labour-driven facility layouts, problem definition, aims and objectives, assumptions and methods that were presented in the thesis to achieve the objectives of the research along with the contributions and conclusions obtained from the research. Figure 1.4 shows the organisation of the thesis and how chapters are interrelated with each other.

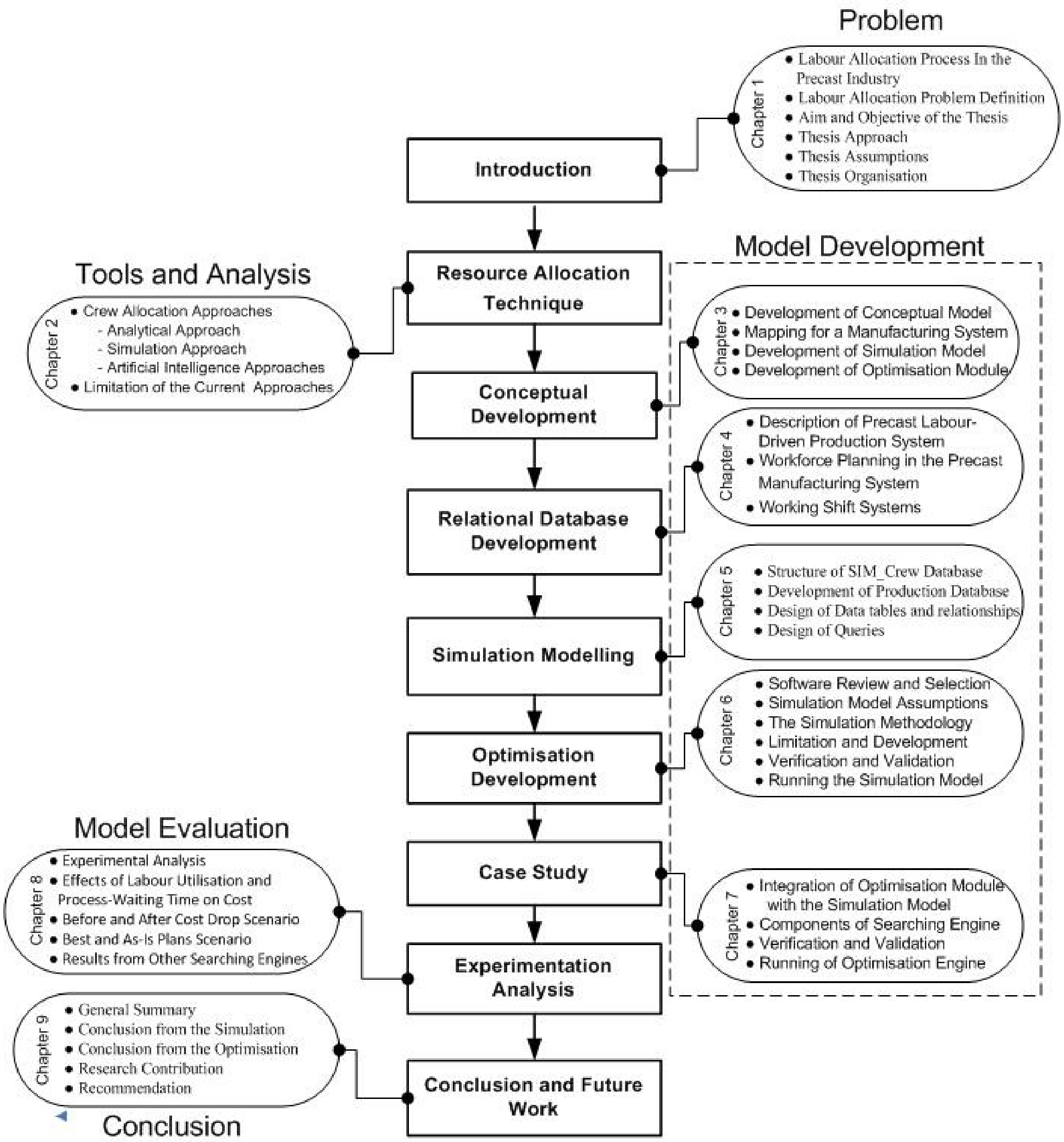


Figure 1.4: Thesis organisation structure chart

The remainder of this thesis has been divided into the following chapters.

Chapter Two: demonstrates a number of tools and techniques used in crew allocation. The outputs from a number of researchers were used to identify these tools and techniques that have already been developed and used to solve the crew allocation problems. A critique is provided to show the gap in current crew allocation techniques, requiring further innovation and research.

Chapter Three: demonstrates the conceptual model of the proposed crew allocation system. The architecture of the system is presented and discussed in detail. The concept of process map modelling is introduced as a system modelling tool. This methodology is used to present the development processes of the crew allocation system. The development process of the simulation module is discussed in detail as one of the crew allocation system's component. In addition, the process of developing the optimisation module is presented and the multi-layer concept is introduced.

Chapter Four: describes the sleeper precast concrete manufacturing systems. Data collection methodology is presented in order to give an idea about how the data was collected. The labour-driven processes of precast production system are described in detail. Workforce planning is presented and explained. A working shift system in the selected labour-intensive production system is explained to outline the difficulties of having more than one shift as a working pattern.

Chapter Five: presents the structure of the developed database for production information was developed alongside an information storage and retrieval system. A relational database model was designed to form the required labour information system and to facilitate the process of storage and retrieval.

Chapter Six: presents the development of a simulation model to imitate a labour-driven production system. A number of simulation software systems are reviewed in order to select the most suitable one. Decomposition simulation methodology is presented to simulate large-scale manufacturing systems. The limitation of the selected software is addressed and discussed in detail; a special template; PROCESS module is introduced as a possible solution for the limitation identified. Verification and validation of the developed model is explained in detail. The running of an “As-Is” scenario is undertaken and some preliminary results are shown. Visualisation of the sleeper concrete labour-intensive system is presented as a promising interactive tool.

Chapter Seven: demonstrates how the optimisation module is integrated with the developed simulation model. A number of algorithms are developed and integrated in order to form the core of the optimisation module. ‘One search’ strategy is developed in order to prevent solution duplications. The mechanism of accommodating a chromosome into a multi-layered structure is presented. Verification and validation of the developed optimisation module is discussed in detail. The running of the optimisation module is undertaken and some preliminary results are shown. Searching algorithms using Monte-Carlo and Simulated Annealing are developed to be embedded within the simulation model for a comparison purposes.

Chapter Eight: illustrates the experimental part of the developed crew allocation system. Effects of optimising labour utilisation and process-waiting time on labour allocation cost are indicated through analysing a number of intermediate results: “Before and After Cost Drop” scenarios and “Best and As-Is” scenarios. A comparison between “As-Is” and best allocation plan is outlined to prove the concept of the proposed allocation methodology. Four experiments are designed to conduct sensitivity analysis and identify control factors that influence the model outputs and performance. A comparison study is made with Simulated Annealing and Monte-Carlo techniques to evaluate the performance of the proposed allocation system using a GA.

Chapter Nine: Summarises the research work. The conclusions drawn from the research, advantages and disadvantages of the adopted methodology, limitations of the research and future recommendations are presented.

1.13 CHAPTER SUMMARY

The workforce planning process in the precast labour-intensive industry has been defined with the benefits of labour allocation process. The problem is defined relating to the precast industry. The aim and objectives of this work have been identified alongside the scope and significance of this work. A thesis organisation structure was outlined and a brief introduction for each chapter has been indicated.

The next chapter addresses resource allocation modelling techniques. Reasons for selecting simulation and genetic algorithms to form an allocation tool are addressed.

CHAPTER 2

SIMULATION AND ARTIFICIAL INTELLIGENCE TECHNIQUES IN RESOURCE ALLOCATION PROBLEMS

2.1 INTRODUCTION

In this chapter, a number of crew allocation tools and techniques are presented. The purpose of presenting such tools is to demonstrate the applicability of each technique in solving crew allocation problems. After demonstrating the strengths and weakness of each technique, the selection of a suitable allocation technique is possible. The allocation techniques are split into three categories: analytical, process simulation and Artificial Intelligence (AI). Analytical modelling capability associated with crew allocation is discussed and a number of mathematical models are presented. Process simulation is presented and explained in detail as one of the most flexible modelling tools that can handle the level of complexity. The application of simulation in a number of manufacturing industries is discussed. The Artificial Intelligent techniques are demonstrated in terms of their applicability in the resource allocation field, by reference to a number of previous and recent research works. These AI techniques are classified into: Tabu Search (TS), Particle Swarm Optimisation (PSO), Simulated Annealing (SA), Artificial Neural Networks (ANN), Ant Colony (AC), and Genetic Algorithms (GAs).
In the next section, the crew allocation techniques are explained in detail.

2.2 IMPROVING PERFORMANCE OF THE PRECAST AND CONSTRUCTION SYSTEMS: PREVIOUS STUDIES

Different aspects of the precast and construction systems have been studied by researchers in order to improve the performance and efficiency of such systems. These aspects are classified into six main categories: (1) production planning and scheduling,

(2) supply chain management, (3) stockyard management, (4) resource allocation, (5) productivity, and (6) process re-engineering. Each categorised research shows: researcher name(s), industry being investigated, focus of the research, and addressed conclusions. See table 2.1 for more details

Table 2.1 Literature review matrix of improving performance of the precast and construction systems

FIELD OF APPLICATION	AUTHOR	INDUSTRY	FOCUS	Conclusions
Production Planning and Scheduling	Chan and Hu (2001)	Precast	Solving production scheduling problem considering constraints encountered in actual practice. A flow shop sequencing mathematical model is developed for production scheduling and Genetic Algorithm is used to optimise it.	• The techniques used involved GA, mathematical models, heuristic scheduling approaches and showed that such tools and techniques can provide and enhance the planning and scheduling process. • The required details of scheduling techniques were presented for such production planning and scheduling problems including detailed schedule plans in terms of order sequence, concrete mould combination, different loading rules, product delivery programme and other key performance indicators involving make span, lateness penalties, total planning-related costs, and short lead-times.
	Dawood (1995)	Precast	Developing a scheduling model that mimics the decision making process of a production scheduler. A heuristic job shop scheduling approach was used to make better planning decisions.	
	Benjaoran et al (2005)	Precast	Optimising production schedules by targeting production planning. A flow-shop scheduling mathematical model was produced and Genetic Algorithms were used to produce economic and efficient production plans.	
	Zhai et al (2006)	Precast	Development of a production planning model for a "make-to-order" precast production with two critical resources. Process simulation and Genetic Algorithms were used to solve the production planning problem.	
	Leu and Hwang (2002)	Precast	Solving flow-shop precast scheduling problem with makespan as the criterion for the constraints of resource limitations and different due days of multiple production packages. A genetic algorithm-based searching technique was adopted for solving such problems.	
	Pérez-Vázquez et al (2007)	Precast	Scheduling of the concrete sleeper manufacturing process problem. A multi-objective deterministic 'crowding' genetic algorithm was developed to solve such a problem.	

Table 2.1: Literature review matrix of improving performance of the precast and construction systems (Cont)

FIELD OF APPLICATION	AUTHOR	INDUSTRY	FOCUS	Conclusions
Supply Chain Management	Vrijhoef and Koskela (1999)	Construction	Applying generic methodology offered by SCM on the construction supply chains for improved understanding. The generic body of knowledge accrued in the framework of supply chain management (SCM) was adopted in order to improve the understanding of the characteristics of construction of supply chain problems, and gave a direction for action.	• Efficient management of a supply chain can be achieved through careful consideration of capacity and material information. The application of simulation in managing a supply chain can assist in providing the required level of awareness of supply chain dynamics and its efficiency over time. • The knowledge obtained from supply chain management leads to improved understanding of the characteristics of SCM problems and provided a guideline for further research activity.
	Ericsson et al (2001)	Construction	Estimates obtained on supply chain costs and project completion times. A simulation model of the constructional supply chain was designed, built, calibrated, tested and validated to obtain the estimates.	
	Cutting-Decelle et al (2007)	Construction and Manufacturing	Review of different approaches to supply chain communications in manufacturing and construction. The main approaches to supply chain communications used in manufacturing industries were reviewed.	
	Chang and Makatsoris (2001)	Manufacturing	Discusses the issues of supply chain management and the requirements for supply chain simulation modelling.	
Stockyard Management	Macro and Salmi (2002)	Manufacturing	Determining warehouse efficiencies and storage allocations. Simulation was utilised as a tool to analyse existing warehouse systems.	• Layout arrangement, allocation of products to storage spaces and stockyard space utilisation for different production plans considered as combinatorial problems. • Simulation and AI tools such as Genetic Algorithms can successfully solve such SCM problems.
	Marasini et al (2001)	Precast	Identifying the appropriate methodology for designing and managing the stockyard layout. A process simulation model was developed to model stockyard layouts and Genetic Algorithms were used to identify more efficient product clusters.	
	Cheung et al (2002)	Precast	Identification of a near optimal site pre-cast yard layout solution. A GA-model was developed to improve the layout arrangement.	

Table 2.1: Literature review matrix of improving performance of the precast and construction systems (Cont)

FIELD OF APPLICATION	AUTHOR	INDUSTRY	FOCUS	Conclusions
Resource Allocation	Nassar (2005)	Construction	Considered resource allocation in repetitive construction schedules. A model was developed using a spreadsheet application and commercial genetic algorithm software to provide a more efficient allocation solution.	• Most of the studies focused on reducing production times, minimising costs, optimising resource utilisation, diminishing idle times but insufficient attention was paid to identifying interchanging relationships between these key performance indicators. • Most systems do not utilise optimisation modules for solving resource allocation problems, only running simulation scenarios for improvement were adopted for such systems (without further optimisation using GA's). • The detailed modelling of labour resources relating to different worker skill levels has not been considered in the current practice of resource allocation.
	Li et al (1998)	Construction	Provided a methodology to labour and equipment assignment. A GA system was developed to be effective in finding global optimal or near optimal resource assignment solutions.	
	Srisuwanrat and Ioannou (2007)	Construction	Considered resource allocation in probabilistic repetitive projects. A simulation model was developed and the optimisation was performed using a genetic algorithm to optimise the overall objective function of project profit.	
	Zhang et al (2004)	Construction	Optimising dynamic crew allocation for construction scheduling. Discrete-event simulation with a heuristic Algorithm was utilised to obtain an improved allocation plan.	
	Vaziri et al (2007)	Construction	Allocation of skilled workers amongst individual tasks for a single project. A mathematical formulation that captured the uncertainty associated with task duration and resource requirements was developed.	
	Dawood et. al (2007)	Precast	Forecasting of production schedules, cost, and productivity. A generic simulation model depicting the operational processes of precast concrete production system was developed.	
	Lam et. al (2008)	Construction	Considered scheduling of skilled labourers in a multi-project context. Particle Swarm Optimiser (PSO) strategy was adopted as a stochastic search strategy to identify the optimal/near optimal schedules.	

Table 2.1: Literature review matrix of improving performance of the precast and construction systems (Cont)

FIELD OF APPLICATION	AUTHOR	INDUSTRY	FOCUS	Conclusions
Productivity	Liu (1995)	Precast	Investigated productivity, resource utilisation, and unit costs. A discrete-event simulation modelling technique was used to model and analyse one of the precast production processes.	• In order to increase construction productivity, it is necessary to model and simulate construction operations and run improvement scenarios that minimise idle time, eliminate bottlenecks, increase productivity, and reduce costs. • Productivity improvement leads to reduced project delivery time and increases productivity whilst providing significant time and cost savings.
	Balbontín-Bravo (1998)	Precast	Considered improving productivity and reducing the production costs. Time-study and work sampling tools were used to measure the machine cycle and human work content respectively and simulation technology was used to model the production of precast products.	
	Halpin et al (1999)	Precast	Increased productivity by reducing project delivery. Simulation modelling was utilised in the modelling phase.	
	Hong and Hastak (2007)	Construction	Determined productivity, man-hour requirements, and system bottlenecks. Process modelling and simulation study were used to determine the productivity and cost per hour of installation processes.	
	Watkins et al (2007)	Construction	Explored the impacts of individual interactions on productivity and labour flow. An agent-based model was designed in which each worker and task was presented as an autonomous agent.	
	Shi et. al (1998)	Construction	Integrated construction time and necessary resource combinations. A simulation model was adopted to mimic the construction process of a flow cycle	

Table 2.1: Literature review matrix of improving performance of the precast and construction systems (Cont)

FIELD OF APPLICATION	AUTHOR	INDUSTRY	FOCUS	Conclusions
Process Re-Engineering	Li (1996)	Construction	Described the basic steps involved in construction process re-engineering. Discussed the role of the IT manager in construction process re-engineering.	• Substantial cost and time savings can be obtained if the right level of process mapping is optimally selected by developing appropriate optimisation models. • Business process re-engineering aims are simplification, elimination and redesigning business processes for greater efficiency and cost reduction.
	Soliman (1998)	Construction	Determined the optimal level of process mapping corresponding to the least cost of process re-designs. A linear programming model was developed to determine the optimal level of process mapping that produces the lowest cost of process re-design.	
	Allweyer et al (1996)	Construction	Discussed the requirements for and outlined a possible approach for business process re-engineering.	

After investigating a number of development aspects for both the construction and precast industries, it was concluded that the resource allocation aspect had not received enough attention in terms of detailed modelling considering different levels of worker skills. Therefore, resource allocation is addressed as a key focus area of this thesis.

2.3 CREW ALLOCATION APPROACHES

In this section, crew allocation approaches are split into three main categories: analytical, process simulation, and artificial intelligence. The application of each approach in resource allocation and scheduling is presented in a number of previous and current studies:

2.3.1 Analytical Approach

During the last 50 years, a number of analytical assignment models have been developed to solve the allocation problems in various industries, Pentico (2007). Some of studies have been conducted in the area of crew allocation, planning, scheduling and modelling of multi-skilled allocation models in labour intensive industries, examples are: Yen and Birge (2006) described a stochastic integer programming model for the airline crew stochastic scheduling problem and the development of a branching algorithm to identify expensive flight connections and to find alternative solutions. The results showed that significant savings in the expected cost of a solution without compromising the overall solution was achieved. Hass et al (2000) presented a mathematical formulation of a multi-skilled allocation model to optimise the allocation and assignment of multi-skilled workers to activities in a construction project. However, shift systems and parallel repetitive activities were not considered in these studies. Vaziri et al (2007) developed a model formulation and a solution procedure to optimally allocate skilled workers amongst individual tasks for a single project. A relationship between worker productivity, size of crew, and task duration was addressed. Sohoni et al (2004) devised a stochastic integer programming formulation to select reserve patterns minimising involuntary flying hours and cost over a finite number of open time trip scenarios.

Although mathematical modelling was used in solving various real life problems, it is still too complex to be used in modelling and solving problems involving shift working, uncertainties, and other issues of this nature. Mathematical models are not flexible enough to easily alert the models, when the results do not provide the expected outcome, Cusack (1984).

Therefore, a mathematical modelling approach cannot be utilised in the modelling of repetitive parallel processes present in the precast concrete manufacturing system. In addition, the modelling of multi-shift workers working in a repetitive parallel process environment is too complex to be modelled using traditional approaches.

2.3.2 Simulation Approach

Simulation is one of the innovative tools used in system modelling issues that has evolved over the past 50 years, Nance and Sargnet (2002). Since then simulation has widely been accepted as a planning and problem solving tool in a variety of domains. It can handle as much detail as is necessary to capture any process. Simulation is considered as a means of evaluating the impact of process changes and new processes in a model environment through the creation of "what-if" scenarios. A number of researchers defined simulation as follows: Hoover S.V., and Perry R.F. (1989) defined simulation as the *"process of designing a mathematical or logical model of a real system and then conducting computer-based experiments with the model to describe, explain, and predict the behavior of the real system"*. Shannon (1998) defined simulation as the *"process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behaviour of the system and/or evaluating various strategies for the operation of the system"*. However, simulation definitions can vary according to the field in which the simulation is used.

Simulation is most useful when analytical and numerical techniques cannot provide the necessary solutions, Lewis and Orav (1989). Previously, simulation was considered as a slow, iterative, experimental problem-solving technique. Sometimes it was referred to as the method of last resort. From a statistical and operational research view point, the term 'Simulation' is essentially a controlled statistical sampling technique (experiment) that is used, in conjunction with a model, to obtain approximate answers for questions about complex, multifactor probabilistic problems (Lewis and Orav 1989). Simulation has a number of purposes that may suit different fields of application, Aburdene, (1988). In order to start simulation, it is important to understand the various types of simulation model and their associated characteristics, Robinson, (1994). There are two broad types of simulation modelling: continuous simulation and discrete event simulation.

The distinction is based on whether the state can change continuously or at discrete points in time. Discrete event simulation models are very popular for modelling a range of real-world systems such as banks, hospitals, and transportation systems. For discrete-event simulation modelling there are three main areas where it is used: event-scheduling, activity scanning and process-interaction, Miller et al (1999).

The event-scheduling approach concentrates on how events affect the system state. The process-interaction approach considers the different entities in the system (e.g. the customers, the server and the arrival generator) and describes the sequence of events and activities that such entities execute or undergo, during these stay in the system. The activity scanning differs from event scheduling in that the condition related with any conditional event should be evaluated after each event occurrence.

Discrete event simulation is one of the most widely used methods to study, model, analyse, design, and improve manufacturing systems, Bodner and McGinnis (2002). In the discrete event methodology, state changes in the physical system are represented by a series of (random) discrete changes or events at specific instants of time and such models are known as discrete event models, Neelamkavil (1987). In manufacturing systems, the completion times of jobs at machines, machine break-downs may be a simple example of a discrete event system. Discrete event simulation was chosen as a methodology to be used in this study.

Simulation like any other modelling tools has many advantages and disadvantages in use, Shannon (1992). Commercial simulation packages can be used as a vehicle to simulate systems. Applications of these packages vary in different fields of applications, see figure 2.1.

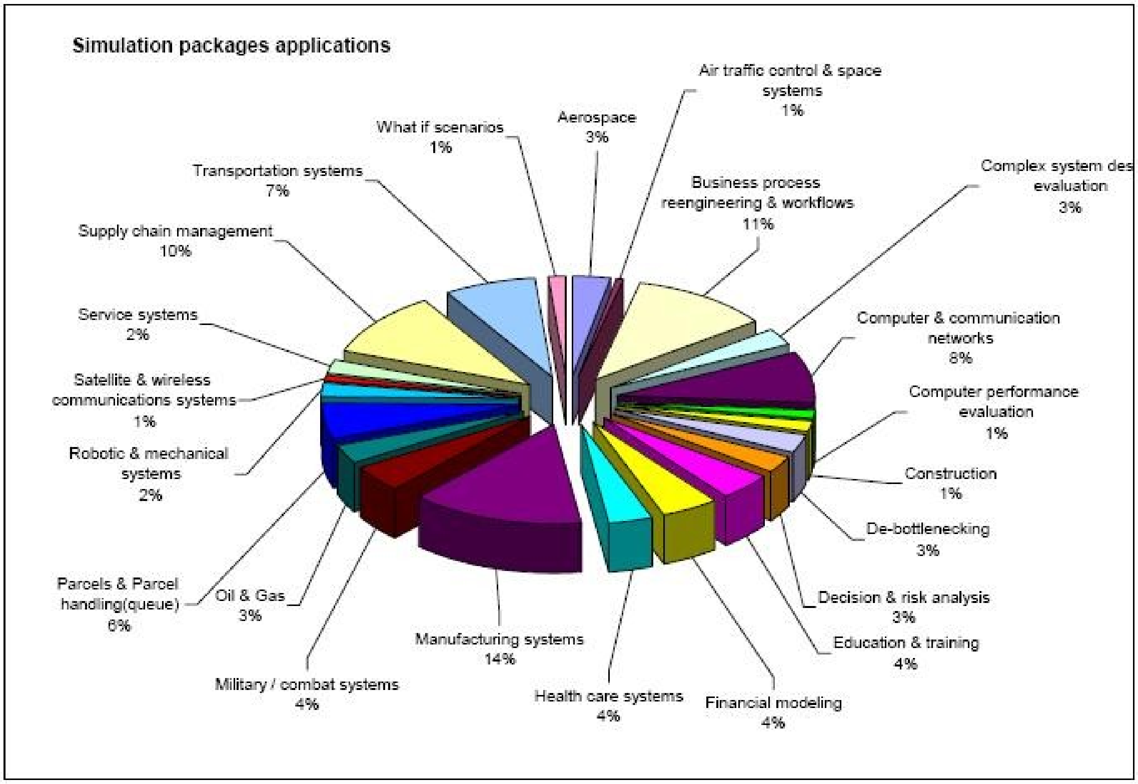


Figure 2.1: Simulation packages applications (Evon et al 2007)

As can be seen from figure 2.1, simulation models are widely used for problem solving in many areas. Some example are: agriculture, aircraft industries, biology and medicine, computer networks, distributed systems, hospital administration, financial modelling, inventory systems, maintenance process, manufacturing industries, policy decision and planning, process industry, resource allocation, and robotics, Neelamkavil (1987). In addition, simulation has been used as:

- A development tool to improve the performance of manufacturing systems (Sim et al 2006).
- A bottleneck analysis tool in order to increase the productivity of the system (Baesler et al 2002, Ucar et al 2006).
- An estimation tool to improve quality and productivity in the manufacturing systems (Türkseven and Ertek 2003).
- A decision support system in order to effectively provide timely information and to assist in management decision making in wood products manufacturing (Kline et al 1992).
- As a universal warehouse storage simulation model in order to analyse storage capacity, and rack utilisation (Macro and Salmi 2002).
- An innovative stockyard layout planning system for a precise stock location in the building products industry (Marasini and Dawood 2001).
- A production planning system (Dawood 1991, Kyle and Ludka 2000).
- A study tool to study the performance of a proposed dispatching algorithm (Gupta et al 1999, Halpin and Martinez 1999).
- A prediction tool to predict potential bottlenecks and to refine resource and process modification (Atia et al 2003).
- An estimation tool to estimate and improve the quality and productivity performance in a manufacturing system (Türkseven and Ertek 2003).
- A detailed overview of simulation in manufacturing design and scheduling with a number of example applications can be found in (Miller and Pegden 2000).

In the area of crew allocation, simulation has been successfully used to model the production of precast units in order to improve productivity and therefore reduce production cost, Bravo (1998). The results showed that the production rate may be improved by adopting different shift alternatives per day with slight losses due to slower adjustment to steel supply. However, production time and other delay factors were not considered. Huanga et al (2009) developed a discrete event simulator named

“SIMMAN”, to serve as a test bed for evaluating the effectiveness and robustness of different planning options and workforce assignment rules. The results validate the earlier argument of delaying the project starting time to reduce the outsource cost as additional manpower can be made available when some of the ongoing projects end.

However working shifts pattern were not considered. Shi et al (1998) adopted a simulation technique for modelling and simulating public housing construction in order to speed up the construction process. The developed simulation model was used to model the construction process of a floor cycle in order to analyse the cycle time and utilisation of resources. The results achieved indicated that crane utilisation reduced and the utilisation of other crews was increased. Cost and other delay related factors were not investigated. Vern and Gunal (1998) developed a simulation model to capture random elements and to facilitate the analyses of complicated “what-if” scenarios within precast concrete building elements. The objective of this study was to investigate production methods with varying degrees of automation in order to alternate crew scheduling strategies, with some animation to facilitate a visual communication tool for analysing the system. Camm et al (1987) provided a general approach to the resource allocation problem in a ‘make-to-order’ production programme. The results indicated that as crew learning improves either production rate increases, or the crew size decreases over time. Marzouk and Moselhi (2004) presented a special purpose simulation model to capture the uncertainty associated with bridge construction. The results showed that increasing the number of labour crews shortens the fabrication duration. However, cost and other delay factors were not calculated. Dawood, et al (2007) developed a generic simulation model depicting the operational processes of precast concrete production system. The developed simulation model encompassed resource allocation planning and a resource utilisation evaluation. The objective of the developed model was to provide planners and manufacturing managers with a tool to forecast production schedules, cost, and productivity. The study of resource allocation policies was the second objective of the developed model. The results showed that if the number of human resources available is reduced, the lead time increases and the production costs reduce, and the greater the number of resources, the shorter the lead time but the production cost increases. However multi-shift resources were not modelled. Kataoka (1992) discussed a railway crew allocation problem and proposed a multi-layer gathering model based on the knowledge-based approach to support schedulers using a computer system. The railway crew allocation system supporting trial and error is commonly used in the railway industry to generate crew service patterns by schedulers. The results obtained indicate that schedulers can generate a crew service schedule with less time and work activity with the developed system. However, there was a need to calculate costs and apply shift patterns on the developed multi-layered model. Alashwal and Abdul Rahman (2008) developed a simulation model to test the proposed layout of precast production lines. The objective of the developed simulation model was to find the optimal line for production setup with a minimum number of available production resources (steel moulds, workers, etc). The results showed that adopting three shifts working against different treatment area capacities resulted a significant reduction in the production time. Although, crew formation, cost and other delay factors were not considered. Guttkuhn et al (2003) introduced a discrete event simulation for crew assignment and crew movement as a result of train traffic, labour rules, government regulations and optional crew schedules. The results of the simulation allowed the user to draw conclusions concerning the operational characteristic of the real crew assignment process.

From the previous studies, it has been noted that the simulation models developed for crew allocation purposes did not use any optimisation modules for better allocation as they were dependent only on repetitive investigation and "what-if" scenarios. However, the explosion caused by the very large number of crew combination involved cannot be evaluated using a simulation approach on its' own. Factors such as: allocation cost, shift patterns, crew formation, different skills, worker utilisations and process idle times were not considered in the design of these simulation models.

2.3.2.1 Reasons for Choosing Simulation Technology in this Study

The following points indicate in detail why process simulation technology was chosen to model the precast manufacturing system being investigated:

(1) The modelling of parallel repetitive processes layout is complex enough in terms of the involved processes and the associated uncertainty.
(2) A large numbers of decision variables are involved in the allocation decision making process which makes the crew allocation process complex enough.
(3) The developed model can be easily adjusted when the results do not reflect expectation.
(4) The alternation of crews of workers in any production process is more easily to be conducted within a simulated process module.

The mathematical programming techniques cannot be utilised in developing the parallel repetitive processes manufacturing system due to the complexity of the crew allocation problem being studied with multiple criteria to be satisfied. The combinatorial relationships and uncertainties involved in the precast industry was the reason why simulation was chosen as a basis solving the industry related problems.

It can be hypothesised that simulation models have the potential to model the parallel repetitive labour-intensive processes. Because simulation is computationally expensive, the optimisation process would be able to search the solution space more extensively if this process is able to quickly eliminate the consideration of low-quality solutions, where quality is based on the performance measure being optimised and hence simulation optimisation is required.

Simulation optimisation is the process of finding the best values of some decision variables for a system where the performance is evaluated based on the output of a simulation model of this system, Ólafsson et al (2002). Simulation optimisation has been used in real-time decision making in order to solve such problems under real-time environment (Zhang 1997), Improving performance of wood processing plant (Baesler et al 2002), more effective allocation of the finished goods in a warehouse (Queirolo et al 2002), multi-criterion scheduling optimisaiton of order picking activities in a warehouse, Molnár (2004). A number of optimisation techniques have been adopted for solving simulation optimisation problems, Krug et al (2002).

However, the purpose of developing an optimisation module to be embedded within simulation models is to add more intelligence to the simulation model so more sophisticated search can be achieved to identify optimal/ near optimal crew allocation plan in a short time. A number of the most common artificial intelligence techniques, used with simulation, are discussed in the next section.

2.3.3 Artificial Intelligence Optimisation Techniques

All parameters of the crew allocation problem considered in this research are discrete since each parameter represents an individual crew of workers and the number of crews or workers should always be an integer (discrete) number. Therefore, a number of discrete parameter optimisation methods based on Artificial Intelligence tools (AI) concept are utilised as discrete searching algorithms, which can possibly be applied in resource allocation problems. The reason of choosing AI tools is their ability to explore solution space in an intelligent way in order to find optimal/ near optimal solutions.

These algorithms can make the simulation or mathematical modelling process less time consuming when searching for good solutions. The applicability of each AI searching algorithm was investigated and the advantages of each algorithm was addressed in order to identify the algorithm that most efficiently can be used in solving the crew allocation problem faced by this research.

2.3.3.1 Tabu Search

Tabu Search (TS) was first presented in its present form by Glover (1986). In 1989, Glover presented the fundamental principles underlying Tabu search as a strategy for combinatorial optimisation problems. Tabu Search (TS) is a meta-heuristic method that can be used to solve combinatorial optimisation problems, Glover and Laguna (1992).

The power of TS derives from its use of flexible memory cycles. These memory cycles control the local search pattern, intensively, and diversity of the search in the quest for a suitable solution. The local procedure is a search methodology that uses an operation called 'move' to define the neighboarhood for any given solution. One of the main components of Tabu Search is its use of adaptive memory, which creates more flexible search behavior, Glover and Laguna (1997). TS is an adaptive procedure with the ability that makes use of other methods such as linear programming algorithms and specialised heuristics, which it directs, to overcome the limitation of local optimality.Tabu search applications range from graphical theory, scheduling, routing, travelling salesman, and mixed integer programming problems.

In the area of crew allocation problems, a few attempts were conducted to evaluate Tabu Search as a solution tool for resource allocation problems. Al-Mahmeed (1996) used Tabu search in solving problems of real-time resource allocation. Murphy (1998) developed an algorithm combining Tabu Search principles with a simple improvement-swapping heuristic for allocating stands and cutting patterns to 'logging crews' for a single time period. In 2008, Pan et al improved and developed TS model to solve resource-constrained project scheduling problems.

Although Tabu search (TS) has provided advantages for solving complex optimisation problems in many domains. The memory used in Tabu search is both explicit and attributive makes this technique more suitable for use in solving complex problems such as problems having a graphical or network settings.

In this study, the nature of the crew allocation problem and specifically the pool of crew alternatives do not require the incorporation of adaptive memory as a procedure to search the solution space effectively. Such incorporation could lead to more difficulties associated with the modelling of crew alternative issues. Although evolutionary techniques such as TS can embody a form of implicit memory which is not easy for incorporating within the crew alternatives pool for the effective solution of crew allocation problems. Other evolutionary procedures that operate by combining solutions are more applicable for modelling such allocation problems

2.3.3.2 Particle Swarm Optimisation (PSO)

Particle swarm optimisation (PSO) is a population based stochastic optimisation technique developed by Eberhart and Kennedy in (1995), inspired by social behavior of bird flocking or fish shoaling. The system using PSO is initialised with a population of random solutions with searches for optima based on updating generations. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles. Each particle keeps track of its coordinates in the problem space associated with the best solution (fitness) achieved so far. PSO obtains better results in a faster, cheaper way compared with other methods and there are fewer parameters to adjust. PSO shares many similarities with evolutionary computation techniques such as Genetic Algorithms (GA). However, unlike a GA, PSO has no evolution operators such as crossover and mutation. PSO has been used for approaches that can be used across a wide range of applications, as well as for specific applications focused on a defined requirement.

One of these applications was the resource allocation application where PSO was utilised in the area of resource-constrained project scheduling, Zhang and Li (2004). PSO was then used by Lam and Lu (2008) to solve the problem of skilled labourer scheduling in a multi-project context. The results showed a substantial reduction in the job duration came solely from improvements in the efficient use of time and the budget.

However, multi-shift patterns and the 'concept of crews' were not used. In 2006, Yin and Wang utilised PSO to solve nonlinear resource allocation problems. None of the above studies were used to model a multi-skilled worker and repetitive parallel processes manufacturing system layouts. This approach could have been used to solve the allocation problem addressed in this research. However, the level of sophistication associated with this method means that the development time would be great and probably could not be justified in this context. This method is more applicable to handling complex robotics and the optimisation of electronic circuits, where the development costs can be recouped more easily.

2.3.3.3 Simulated Annealing

Avello et al (2004) defined simulated annealing as *"a meta-heuristic technique that proved to be effective as a solving solution for a number of problems, amongst them, simulation optimization problems"*. Kirkpatrick et al (1983) proposed that SA form the basis of an optimisation technique to solve combinatorial problems.

SA exploits an analogy between the way in which a metal cools and freezes into a minimum energy crystalline structure (the annealing process) and the search for a minimum in a more general system; it forms the basis of an optimisation technique for combinatorial and other problems. SA starts with an initial solution, and moves from one solution to the next, hopefully converging on the global optimum. All such random search methods may only reach a local optimal solution and SA attempts to rectify this by accepting inferior solutions with certain probability and thus allowing the search to escape local optima, Ólafsson and Kim (2002). SA approaches the global maximisation problem similarly to using a bouncing ball that can bounce over mountains from valley to valley. It begins at a high "temperature" which enables the ball to make very high bounces, enables it to bounce over any mountain to access any valley, given enough bounces. As the temperature, declines the ball cannot bounce so high and it can settle to become trapped in relatively small range of valleys.

A number of studies have been carried out in the application of SA as a solution tool in the labour allocation problem: Brusco' and Jacobs (1993) presented a heuristic based-simulated annealing framework for developing labour allocation system. Nussbaum' et al (1998) presented the key elements of approximation methods similar to Hill Climbing, Simulated Annealing, and Tabu Search, were combined together in a tool to appropriately solve sequencing and resource allocation problems.

SA was used to optimise resource allocation of large production line, Spinellis et al (2000), resource scheduling, Cave et al (2002). SA was modified by Schwarzfischer (2003) to produce high quality schedules of a real scheduling problem. Resource-constrained project scheduling is developed using the SA, Bouleimen et al (2002). Chen, P.-H. and Shahandashti S.M. (2007) used Simulated Annealing to optimise linear scheduling projects with multiple constraints. Dohn et al (2009) solved the Manpower Allocation Problem with Time Windows, Job-Teaming Constraints and a limited number of teams, which is a crew scheduling problem faced in several different contexts in industry, by a software tool built on a Simulated Annealing heuristic. The number of teams was predetermined; hence the objective was to create a schedule that will maximise utilisation by ignoring a few tasks. However, cost and shift patterns were not considered. Hamm et al (2009) developed Pareto Simulated Annealing to deal with several optimisation objectives in order to determine near-optimal construction schedules.

A disadvantage of SA is that it is computationally-expensive. Faster variants of basic simulated annealing exist, but these are not as easily coded and hence they are not widely used. The ability of Simulated Annealing to determine a global optimum, even in the occurrence of frustration, makes it a useful tool for image reconstruction, IC circuitry design, mechanism synthesis, path generation, and scheduling.

From the studies above, it was noted that the relationship between a number of performance criteria was not taken into consideration. In addition, multi-shift skilled resources in; parallel repetitive labour driven processes were not addressed.

Simulated Annealing can be used to model and solve the crew allocation problem being investigated. Although Simulated Annealing and Genetic Algorithms are quite close relatives, the nature of the problem and the problem as presented was taken into consideration while choosing the selected searching algorithm.

By using simulation modelling as a module in the proposed system architecture, investigating a population of crews can be evaluated easier by the simulation engine, rather than mutating or replacing the same chromosome to be fed to the simulation engine. This process is time expensive as creating a chromosome each time before testing takes considerable time. However, this technique was chosen to be compared with the selected GA searching algorithm and the Monte Carlo method.

2.3.3.4 Artificial Neural Networks

A Neural Network (NN) is a computational model inspired by the way biological nervous systems, such as the brain, process information. An NN is adaptive since it can learn to estimate the parameters of a population using a small number of exemplars at a time, Abdi, et al (1999). Learning in biological systems involves adjustments to the synaptic connections that exist between the neurones.

The way neural networks process information works is similar to that which the human brain does in terms of information transmission. The network is composed of a large number of highly interconnected processing elements (neurones) working in parallel to solve a specific problem. NN's have the ability to implicitly detect complex nonlinear relationships between dependent and independent variables, and have an ability to detect all possible interactions between predictor variables, alongside the availability of multiple training algorithms. The disadvantages of this type of technique are: its "black box" nature, greater computational burden, minimising over-fitting requires a great deal of computational effort and the sample size has to be large. An AN is essentially configured for a specific application, such as pattern recognition or data classification, parameter estimation, predication through a learning process.

Application of Artificial Neural Networks is limited in solving a number of crew scheduling problems which have a network representation: Lagerholm et al (2000) used a ‘Potts feedback neural network’ approach to find good solution for airline crew scheduling problems resembling real-world situations. Resource allocation in portfolio selection, Ko et al (2008), and the resource allocation in cellular wireless systems, Sandhir et al (2008) were considered as other ANN applications in the resource application area.

The proposed concept applied in this study does not require a learning process, which is the true attitude of an ANN. The relationship between inputs and outputs is not important rather than just identifying a correct set of inputs, which lead to best output. However, complexity yielded by estimation of weights and parameters required to solve the ANN is another challenge consideration when solving crew allocation problems.

2.3.3.5 Ant Colony

Ant Colony is an efficient meta-heuristic approach to solve routing problems that can be presented in terms of graphs with thousands of vertices and millions of edges, or travelling salesman problems with several thousands of cities. The first ACO system was introduced by Marco Dorigo in his Ph.D. thesis (1992), and was called Ant System (AS). AS was initially applied to solve travelling sales-man, and quadratic assignment problems.

This searching approach (ACO) can be used to solve the quadratic assignment problem (QAP) as an exception in the class of combinatorial optimisation problems, of the type this approach is required to solve. Problems of this nature can be found in telecommunication networks, travelling salesman and graph colouring, for example. It has the potential for use in solving job-shop scheduling problems and it was found that Ant Colony had shortcomings regarding the ability of the local search, which can be overcome by integrating it with other searching algorithms such as Taboo search to increase the capability of the hybrid system as a good local search algorithm, Song, et al (2006).

In the area of crew allocation, Lo and Deng (2007) proposed an Ant Colony Optimisation (ACO) based Ant Crew Scheduling Model (ACSM) to solve airline crew scheduling problems. In the proposed ACSM, airline crew scheduling problems were first formulated as travelling salesman problems with flight graph representation. Then, the ACO algorithm was applied to search for near-optimal solutions in airline crew schedules. Nonlinear resource allocation problems, Yin and Wang (2006) and the optimisation of resource allocation in manufacturing projects, Ming et al (2007) were considered as ACO applications in resource scheduling in which the transformation of these problems into a travelling salesman format was required for solving them.

The manufacturing system being investigated in this study cannot be represented graphically. In addition, the nature of the problem is the manipulation of crews of workers to processes which neither the first is considered as a source nor the second as a destination. Distance which should be considered between those targets does not exist. Hence the essential modelling requirements using Ant Colony technique are not satisfied in the problem being modelled.

2.3.3.6 Genetic Algorithms

Genetic Algorithms (GAs) were invented by John Holland in 1960s and further developments were made by the mentioned scientist and a number of his students and colleagues at the University of Michigan between the 1960s and the 1970s.

Genetic Algorithms are search algorithms based on the mechanics of natural selection and natural genetics. They combine survival of the fittest amongst string structures with a structured yet randomised information exchanges to form a search algorithm with some of the innovative flair associated with human search, Goldberg (1989). Genetic Algorithms, are powerful and broadly applicable stochastic search and optimisation techniques, and are perhaps the most widely known types of evolutionary computation methods in use today, Gen and Cheng (2000).

GA searches the solution space by building and then evolving a population of solutions. The evolution is achieved by means of mechanisms that create new trial solutions from the combination of two or more solutions that are in the current population. Transformation of a single solution into a new trial solution is also considered in these algorithms. The main advantages of evolutionary approaches in general is that they are capable of exploring a larger area of the solution space with a smaller number of objective function evaluations, provided that they are implemented effectively.

The genetic algorithm maintains a population of individuals for each generation. Each individual represents a potential solution to the problem under investigation. Each individual is evaluated to give some measure of its fitness. Some individuals undergo stochastic transformations by means of genetic operations to form new individuals.

There are two types of transformation: mutation, which creates new individuals by making changes in a single individual, and crossover, which creates new individuals by combining parts from two individuals. New individuals, called offspring are then evaluated. Figure 2.2 shows an overall view of the Genetic Algorithm model, Sandqvist (2002).

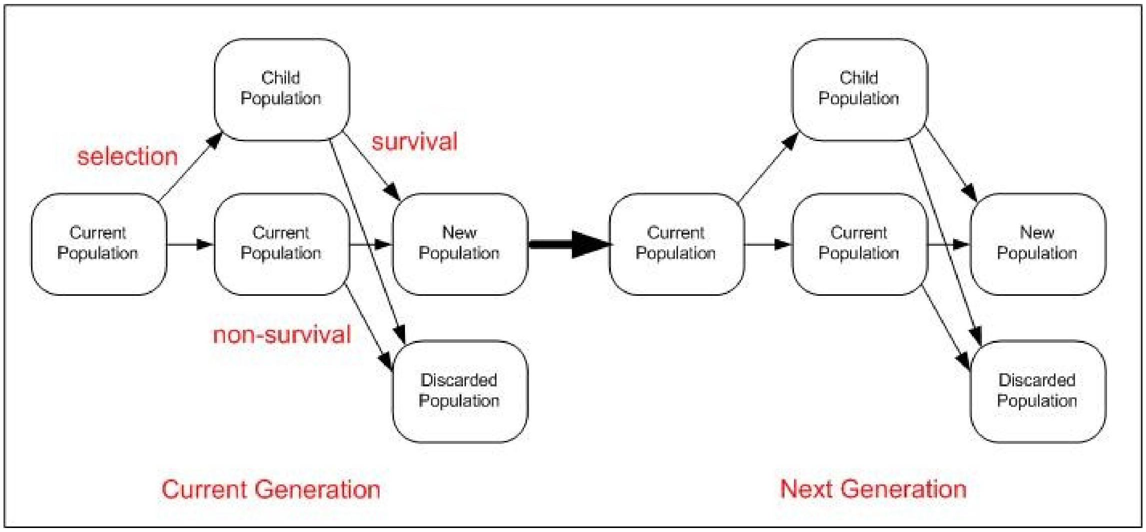


Figure 2.2: Genetic algorithm overview (Sandquist 2002)

A new population is formed by selecting the most fit individuals from the parent population and the offspring population. After several generations, the algorithm convergences to the best individual, this hopefully represents an optimal or suboptimal solution to the problem, Gen and Cheng (2000). A GA is a class of algorithms that are interesting in their own right; a GA was not originally developed as an optimisation algorithm, and the basic GA does not offer any statistical guarantee of global convergence to an optimal point, Lahiri and Chakravorti (2005). Genetic Algorithms (GA) are similar to generic random search but work with a population of solutions rather than with a single solution, In addition, the main innovative contribution of a GA is the novel construction of a neighboarhood based on natural selection principles, Ólafsson and Kim (2002). In conventional genetic algorithms, the crossover operator is used as the principle operator and the performance of a genetic system is heavily dependent on it. The mutation operator, which produces spontaneous random changes in various chromosomes, is used as a background operator, Cheng, et al (1995).

Genetic Algorithms are applied to solving a large range of types of problems, the optimisation problem is one problem, Genetic Algorithms have been used in a wide variety of optimisation tasks, including numerical optimisation such combinatorial optimisation problems resource planning and scheduling such as solving of production-scheduling problems, Knosala and Wal (2001) and concrete delivery scheduling, Lu and Lam (2005). Genetic Algorithms have been modified to solve other production scheduling problems, Pérez-Vázquez, et al (2007).

Before beginning the demonstration of GA operators and in order to have the correct chromosomal representation for the problem, decision variables should be coded before placing them into the chromosome. After coding takes place, the initial population can be generated to facilitate an initial starting solution. The procedure of developing a GA model can be defined as follows:

- **Chromosome Engineering and Encoding**

When applying Genetic Algorithms to computer science and because of the chromosome concept defined in GA, each individual in the search space needs to be encoded and well constructed so that it can be considered of as a chromosome. The purpose of coding is to facilitate the exchanging of gene information using GA operators for more randomness. Encoding depends on the problem type.

- **Population Initialisation**

The first step in a Genetic Algorithm is the random generation of the first population of individuals. The GA starts with a population of strings in order to generate successive populations of strings afterwards. The initialisation is done randomly and mostly using Monte Carlo (MC) sampling to generate random variates with equal probability of occurrence. A large number of methods have been developed to generate the initial population of genetic algorithms (Karci 2004, and Maaranen, et al 2007)

- **Selection of a Chromosome**

The principle behind Genetic Algorithms is essentially a Darwinian natural selection. The selection process provides the driving force in a genetic algorithm to select the most promising chromosomes. With too much force, the genetic search will terminate prematurely, with too little force; the evolutionary progress will be slower than necessary. The selection process directs the genetic algorithm search toward promising regions in the search space. Selection methods have been proposed, examined, and compared over the past two decades; "Roulette Wheel selection" is the best-known selection type, which was proposed by Holland (1975). The basic idea being to determine selection probability or survival probability for each chromosome proportional to fitness value. Then a model roulette wheel can be produced displaying these probabilities. "*The selection process is based on spinning the wheel the number of times equal to population size, each time selecting a single chromosome for the new population"*, Gen and Cheng (2000).

Reproduction is the process in which individual strings are copied according to their objective function values to the next generation pool, Goldberg (1989).

- **Crossover Operator**

The crossover operator is concerned with producing offspring solutions for the next generation from two parent solutions from the current generation. Crossover combines the features of two parent chromosomes to form two similar offspring by swapping corresponding segments of the parents, Michalewicz (1994).

- **Mutation Operator**

Mutation is the way of creating new individuals from the population by achieving a minor change in one or more, gene information attributes for existing individuals. This operator used for avoiding an un-matured solution and to add more randomness to the searching process.

- **Evaluation Process**

After every generated population, every individual in the population must be evaluated by a mathematical or simulation model so that the most likely one can be selected. This is done by comparing the individuals with the fitness function.

- **Termination Condition**

A range of approaches can used to stop a sequence of successive population generations depending on the form of the response surface, the quality of the desired optimal solution, and the assigned computation time.

In GAs, potential solutions required in a problem are represented as a population of chromosomes and each chromosome stands for a possible solution, in hand. The chromosomes evolve through successive generations. Offspring chromosomes are created by merging two parent chromosomes using a crossover operator, or modifying a chromosome using a mutation operator. During each generation, the chromosomes are evaluated with respect to their performance according to the fitness functions (i.e. objective functions). Fitter chromosomes in the new generation may be identical, or certain termination conditions are met. The final chromosomes, hopefully, represent the optimal or near optimal solutions to a problem, Leu and Yang (1999).

Examples of applications of Genetic Algorithms in the area of crew allocation are: Hegazy et al (2003) developed a GA-optimised simulation planning approach to determine the least costly, and most productive, amount of resources for the highest cost/benefit ratio in individual construction operations. The results showed that minimum cost is associated with slightly lower production rate. However, time was not considered as an influential factor on the allocation process. Zhai (2007) proposed a simulation-GA based production planning model for "make-to-order" precast production with two critical resources, moulds and labour. However, crew formations were not considered in the calculations. Li et al (1998) presented a methodology for optimising labour and equipment assignment for excavation and earth work tasks using a Genetic Algorithm (GA) approach. The results showed that the lowest cost solution was achieved. It was noted, that time and other delay factors were not considered. Moselhi and Alshibani (2007) proposed a new methodology for planning, tracking and control of earthmoving operations utilising combined Genetic Algorithms and spatial technologies for optimisation of crew formations for earthmoving operations. The results showed that the use of spatial technology (GPS) for data collection provided project teams with a timely, inexpensive, and accurate monitoring tool. Detailed crew formation and utilisation were not considered in this study. Souai and Teghem (2009) developed a genetic algorithm model to solve simultaneously airline crew-pairing and rostering problems. Two versions of crossover operator called respectively, ‘simplified’ and ‘probabilistic’ crossover were developed to achieve the required swapping process between each pair of individuals. However, both crossover operators were designed for a uni-chromosome structure. Patel (1997) developed an optimised GA based heuristic to solve both dual resource constrained problems. Firstly-Genetic Algorithms were used to determine the optimal staffing level which could be viewed as a basic design decision. A second set of Genetic Algorithms was used to make short range control decisions regarding the operations of a dual resource constrained shop. Kornilakis and Stamatopoulos (2002) developed a Genetic Algorithm model to solve the airline Crew Pairing Problem (CPP). The purpose of the CPP was to generate a set of pairings with minimal cost, covering all flight legs that the company had to carry out during a predefined time period. Delay time was not considered as an influential factor. Orsoni (2004) used Artificial Intelligence (AI) techniques based on Genetic Algorithms (GAs) and simulation to optimise resource allocation to workgroups in labour intensive industrial and business contexts. The results showed that comparable levels of service and worker satisfaction can be achieved involving considerably less resource/overtime cost by carefully reallocating a set of currently available resources. However, parallel labour-driven processes were not considered. Kotecha, et al (2004) presented a genetic algorithm (GA) using new Cost-based Uniform Crossover (CUC) for solving Set Partitioning Problem (SPP) efficiently. The Set Partitioning Problem (SPP) is generally used to represent the airline crew scheduling problem mathematically.

The focus of the aforementioned research efforts was placed on optimising the allocation process of resources. The problem of allocating crews under a multi-shift environment was not considered. The problems associated with adopting multi-shift working in a number of labour intensive industries such as construction and precast are very common.

The allocation process of crews to processes for more than one working shift has not been considered yet, in the precast and construction industries. The application of different sets of multi-skilled operator utilisations has not been classified to identify the performance and effects of each skilled category in terms of utilisation, in all previous studies. In addition, the relationship between numbers of performance criteria has not been tackled in terms of identifying its effect on the total allocation cost. In addition, the delay caused by sharing resources was not considered. Therefore, there is clear requirement for an innovative allocation system that can address the utilisation issue and its relationship with process-waiting time to identify the impact on allocation cost.

The multi-layer concept was introduced in order to simplify the modelling of crew allocation in a multi-shift pattern. The proposed system was designed to present clearly the worker utilisation and process-waiting time factors. Since these are influential factors, that affect labour allocation cost. All previous systems developed to contribute in resolving the issues highlighted do not have this capability.

2.3.3.7 Reasons for Selecting Genetic Algorithms in this Study

A number of reasons motivated the selection of Genetic Algorithms as the optimisation engines of the crew allocation problem being considered are addressed. The following points indicate in detail why a GA was chosen as an optimiser engine:

- GA optimisation algorithms can be tuned easily to enhance their performance and since they do not take time and effort to develop familiarity with a given code.
- GA is a population based meta-heuristic algorithm so more than one solution can be tested at once to shorten evaluation time and save effort.
- The basic mechanism of a GA is so robust that, within wide margins, parameter settings are not critical.

- It can quickly scan a vast solution set because of its ability to test more than one single solution by considering genes of solutions.

- It is a parallel system because parents have multiple offsprings thus making it ideal for large problems where evaluation of all possible solutions in serial would be too time consuming, if not impossible.

- Chromosome engineering is very flexible in terms of involving any number of layers within a chromosome. This type of multi-layer chromosome structure enables different types of data to be coded and accommodated in each layer.

- In the problem being investigated, an optimal allocation of 'crews of operators' to 'labour-intensive processes' is needed to be chosen from a large pool of crews. Genetic Algorithms deal with this type of searching rule as the population of crews can be coded in terms of chromosomes then each chromosome can call the most appropriate crew by referring to its index. Testing of more than one solution is needed to explore the vast solution space.

- Searching operators in such algorithm can be modified easily to suite the searching process of a good solution, for any real life problem. The exploration capabilities can be improved by modifying searching operators.

2.4 GAP IN THE LITERATURE

In this section, a brief critique of the approaches considered in the research has been provided based on the contents of the previous section. The aim was to identify any drawbacks in the current approaches in terms of modelling crew allocation process.

The studies above presented a whole range of methodologies and tools used so far to plan, schedule and allocate labour crews across a range of industries. Previously developed crew allocation systems were incapable of determining the utilisation of each individual worker, as they are only able to produce average crew utilisation. In addition, calculating the utilisation of each skilled category was not possible. This type of categorised utilisation is very important in identifying the performance of different skilled workers. Therefore, there is a pressing requirement for advanced systems that can address this utilisation issue and its relation with process-waiting time to identify their double impact on allocation cost. Most of the studies focused on minimising costs without paying enough attention to the effects of resource utilisation and process-waiting time on resource allocation cost. A few studies demonstrated the simulation of repetitive processes but the detailed crew formation of each process was not taken into account.

Some allocation systems did not use any optimisation modules for better allocation and depending only on repetitive investigation and "what-if" scenarios. In addition, performance key indicators such as cost, waiting time and utilisation were not calculated together, to show their exchange effects on system performance. Developing mathematical models for such problems may be difficult due to the probabilistic nature associated with a manufacturing system's components. However, the modelling complexity of different manufacturing systems appears when their systems have a large scale size, a number of repetitive processes, as well as the size explosion caused by the huge combinations of crews involved. The proposed system considered the worker utilisation and process-waiting time factors as influential factors that can affect on labour allocation cost, and significantly advances capability in the search for optimisation.

Previous GA multi-layer efforts in the previous studies focused on decomposition of problems into a number of sub-problems; each sub-problem being stored into a layer, the purpose of such decomposition was to facilitate the solution of complex problems. In this study, the proposed multi-layer concept is different to previous or parallel efforts by its' use of a multi-layer chromosome storing different sets of input variables

It can be concluded that there is a design/research gap in the application involving the application of optimisation tool for labour-intensive industries that include each crew member in terms of his/her qualification, performance and utilisation. Furthermore research is required to develop approaches that effectively participate in crew allocation problems in other labour-intensive manufacturing systems.

2.5 CHAPTER SUMMARY

In this chapter, process simulation was presented as an innovative technology used in this research and it has been explained in detail. In addition, advantages and drawbacks of using such tools were addressed alongside types of simulation approaches. The limitation of simulation capabilities in terms of searching has been addressed and requirement for an optimisation engine is identified. The reason behind the process of coupling optimisation technology with simulation models to enrich the capability of searching was explained; the resulting optimisation technology was presented in detail.

Artificial Intelligent tools were presented to show the applicability of each of them to resolve such problems. A Genetic Algorithm model was selected as a suitable optimisation module to be coupled with simulation technology. The requirements of developing a Genetic Algorithm model were addressed in detail. The suitability of each AI tool to solve the crew allocation problem being investigated was considered in terms of its' capability for use. A gap in knowledge was identified after a comprehensive review of each AI technique had been undertaken. The reasons behind selecting a GA as a solution tool were addressed in detail.

The following chapter will describe the research problem in more detail.

CHAPTER 3

DEVELOPMENT OF CREW ALLOCATION SYSTEM

3.1 INTRODUCTION

In this chapter, development process of the conceptual model of the crew allocation system is presented. Processes used to design the allocation system are demonstrated in such a way that all inputs, resources, constraints and outputs of each process are clearly defined using the IDEF0 modelling approach for this purpose.

Data collection and logic modelling techniques used to produce the required inputs and process logic are presented. The crew allocation system architecture was developed to demonstrate how the system components are related with each other. Both the simulation methodology and the model architecture are presented to develop the simulation model. A modified Genetic Algorithm model is developed to be embedded into the simulation model. In the modified model, a chromosome structure, selection rules, crossover, and mutation operators were tailored to suit the allocation problem being investigated. The method of embedding this modified model into the simulation model is demonstrated.

The theoretical aspects of each component of the allocation system are discussed. These aspects involve: development of the model specification, development of the simulation model, and development of the optimisation module. In the next section, the conceptual model of the crew allocation system is presented.

3.2 THE CONCEPTUAL MODEL FOR CREW ALLOCATION SYSTEM

A conceptual model was developed to show how all components of the integrated system can work together in order to process inputs and produce outputs. The purpose of developing such a model was to indicate how crew allocation system components can be designed in a way that the correct and most suitable 'crews of workers' can be assigned to the right processes so that minimum crew allocation cost can be achieved. To satisfy the above allocation process objective, a conceptual model was developed which involves integration of simulation technology and Genetic Algorithms as a processing core as shown in figure 3.1

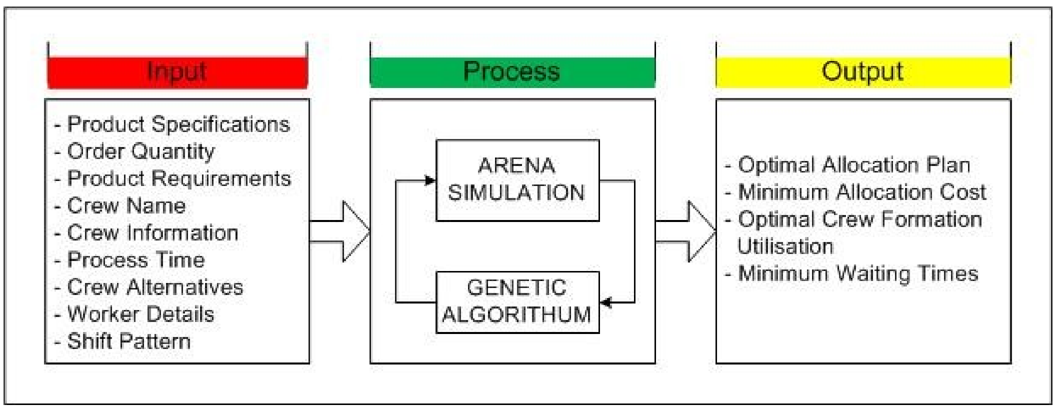


Figure 3.1: Conceptual model for the Crew Allocation model

The inputs, processes, and output presented in the conceptual model (figure 3.1) are introduced and discussed as follows:

- **Inputs**

Order specifications, to be produced in each labour-intensive production line at each section, were identified. All production information involving product type, order quantity, and other requirements such as amount of concrete required to produce a product were stored in an Excel spreadsheet. Labour information such as crew alternatives, formations, process time of each crew, worker details (name, skills, working shift, bonus, and wage) were stored in an Access database; the skills needed for each process were already determined by identifying the crew formation. All labour information being stored in an Access database. A relational database was developed to store and retrieve any information regarding crews, workers, crew processing time, and other worker related information such as skill, cost and other similar information.

- **Process**

In this study, a hybrid system methodology was used to identify the optimal crew allocation plan. The core of the process consisted of simulation and optimisation modules. The combination of simulation and optimisation can be defined as the process of finding the best set of input variables without evaluating each possible alternative of inputs, Molnár (2004).

Process simulation and Genetic Algorithms were integrated together such that production and labour inputs could be processed to obtain promising allocation outputs. The Genetic Algorithm model was designed to be embedded into the simulation model. This type of integration was selected because it can be used to increase the searching capabilities of simulation and subsequently achieve a fast approach to the optimal solution.

- **Outputs**

As shown in the conceptual figure diagram previously (figure 3.1), a number of performance criteria such as labour allocation cost, process-waiting time, and utilisation of labourers were considered as outputs. Each set of outputs (possible allocation plan and other performance criteria) being stored into the Access database for further analysis. The performance criteria include:

- Total resource allocation cost
- Skilled labourer utilisation
- Process-waiting time
- Optimal crew allocation plan.

Outputs were designed to identify the most useful performance criteria that fairly reflected the performance of the developed system.

3.3 THE ARCHITECUTRE OF CREW ALLOCATION SYSTEM

The 'SIM_Crew' architecture (Figure 3.2) comprises a central simulation model integrated with databases and optimisation (genetic algorithms) modules enabling various possible allocation plans to be evaluated by simulating the allocation process of crews to production processes and then stored in a database for further analysis. See figure 3.2 for the system architecture.

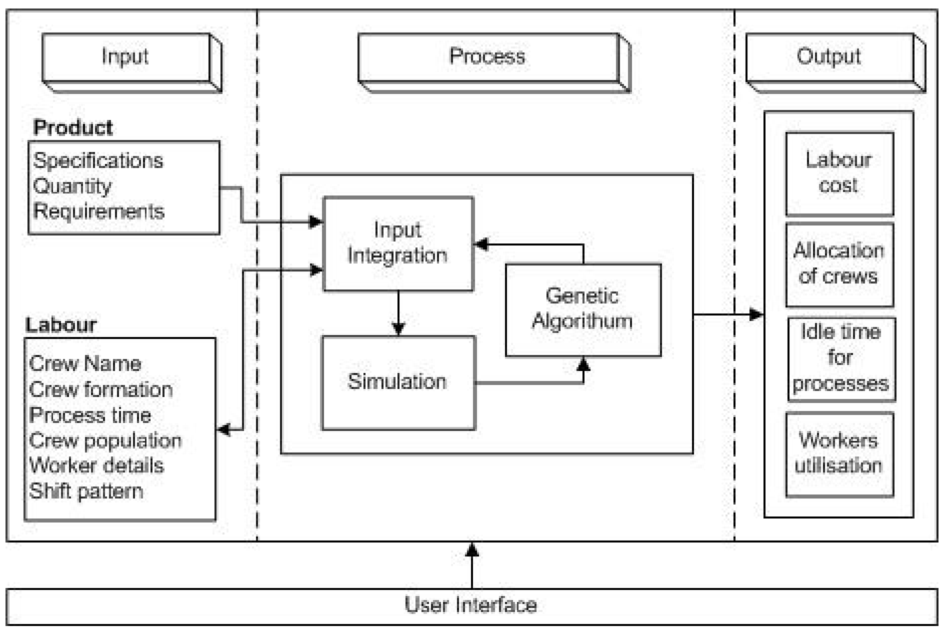


Figure 3.2: 'SIM_Crew' Architecture

The model consists of a user-interface; which was designed to include general information, optimisation parameter settings, and other solution options (discussed in chapter 7, section 5.1). Production and labour information being the data inputs of the model. These inputs being stored into databases (product specification was stored in an Excel database and labour information in an Access database). The inputs were provided to the simulation model through input integration process which consisted of a number of integration technologies including ActiveX Data Objects (ADO) and Data Access Objects (DAO) technologies.

The information from the Access database did not directly constitute the inputs; the inputs to the simulation model were derived from the databases using queries to determine the required set of labour information. Each set of inputs was then processed to determine its performance; this performance was returned to the optimisation engine in order to derive and generate more promising solutions depending on the current performance of solutions.

The function of the optimisation engine was to provide simulation with high quality inputs of feasible allocation plans for a better performance. Beside integration with databases, the integration of simulation and genetic algorithms was achieved through an input integration process. This process consisted of developing the necessary special computer codes required to achieve such integration. 'Genetic Algorithms' generated allocation plans which consisted of a set of crews to be allocated to a number of processes. The formation of each crew was defined and retrieved from the Access database before any evaluation takes place. The proposed allocation plan was then evaluated using the simulation engine.

The optimisation process is an iterative procedure of progressive improvement in which each possible allocation plan proposed by Genetic Algorithms was evaluated by the simulation engine. During one allocation iteration, the simulation engine executed the allocation plans while GA evaluated the performance of the resultant allocation, and based on this, adjust the decision variables and select the most promising ones. After iteration, the results of the evaluation in terms of time, utilisation, waiting time, and cost were stored in a database for further analysis.

3.4 DEVELOPMENT PROCESSES OF THE CREW ALLOCATION SYSTEM

In this section, a process development diagram of the allocation system is presented. The developed process diagram was necessary to demonstrate the processes that were applied to form the allocation system, see figure 3.3

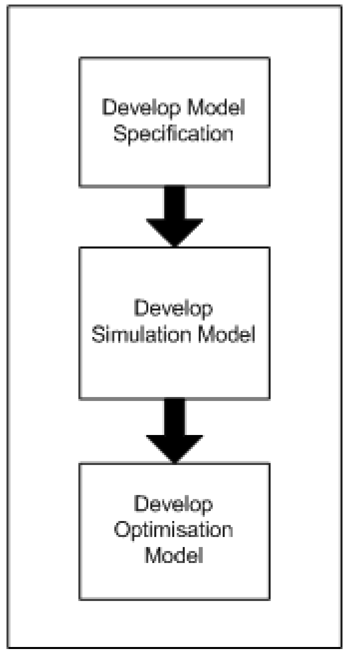


Figure 3.3: development processes of 'SIM_Crew' System

In figure 3.3, the first process towards developing the crew allocation system begins with developing a model specification in which data collection tools and techniques are identified. Seven site visits including fourteen structured interviews were conducted to collect the required information (see *appendix K*). Other logic identification techniques such as process mapping and flowcharting were additionally developed and used. Process maps outlining the logic of each process and the relationships between processes, were prepared by conducting structured interviews and numerous site visits.

A number of reviews of the developed process maps and data were conducted with process related key people to improve and verify the designed process map and all other collected information.

After compiling process maps with related logic, the development of the simulation model was possible (explained in chapter 3, section 5). Using this process, all the process related logic was developed. In the simulation modelling, the developed process logic was translated into a dynamic model.

The development of the optimisation process was the last process in optimising the performance of the developed simulation model and identified the optimal scenario (best set of inputs), (explained in section 3, section 6). The optimisation module was designed to be embedded into the simulation model. The development of model specification is explained in more detail as in the following subsection.

3.4.1 Develop Model Specification

This was the first process of developing the crew allocation system. In this process, a number of tools and techniques were used in order to collect data and to identify the flow and logic of the manufacturing process. The development process comprised four stages, in each stage, a number of tools and techniques were used, see figure 3.4

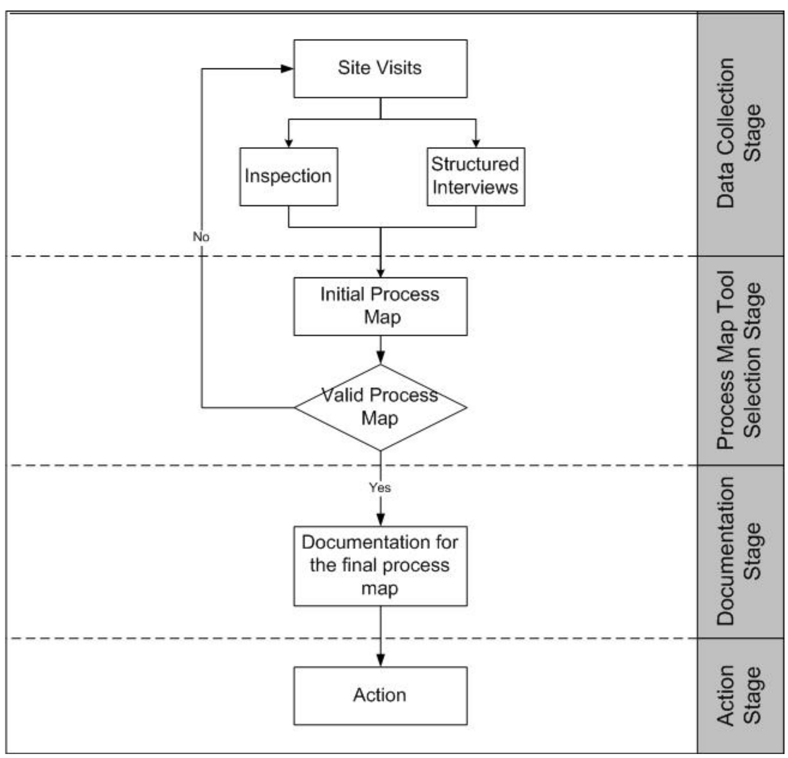


Figure 3.4: Model specification development stages

The **first stage** of model specification development starts with data collection. Several techniques were used to collect the required amount of data including: site visits, structured interviews, inspection. The **second stage:** was the development of a process map. In this stage, an IDEF0 diagram was chosen to model the functions of the system's processes. It was chosen because IDEF0 can be used to develop rich process description and to facilitate the modelling of the system as a complex system (Jeong et. al 2009). An initial process map was developed during this stage, where analysis showed that the modelled information was not sufficiently representative then, additional visits and interviews were organised to verify the process maps. Once the process-map was considered as sufficiently representative, then, the documentation process was considered as completed in the **third stage**.

In the **fourth stage**, discrete event simulation methodology was used to simulate the production processes of the precast labour-driven facility. A 'Genetic Algorithms Model' was developed to optimise the allocation process of assigning crews to processes. A range of documentation tools were used to document simulation models as a means of communicating and storing knowledge over the manufacturing system life cycle presented by (Oscarsson and Moris, 2002).

In order to develop a generic precast process map, three precast concrete companies (company names cannot be mentioned for confidentiality reasons) participated in the development. The first company specialised in pipe and manhole production. The second company was engaged in producing concrete ducting and similar products while the third one was one of the largest companies producing concrete sleeper products. The manufacturing system of each company was investigated in order to collect the required logic and data. The adopted methodology in the investigation was: site visits to each company, with structured interviews carried out during the visit. Statistics for each precast company in terms of visits, number interviews, and the time spent for each interview is given in *appendices C-E*. A summary of the visit statistics is shown in figure 3.5

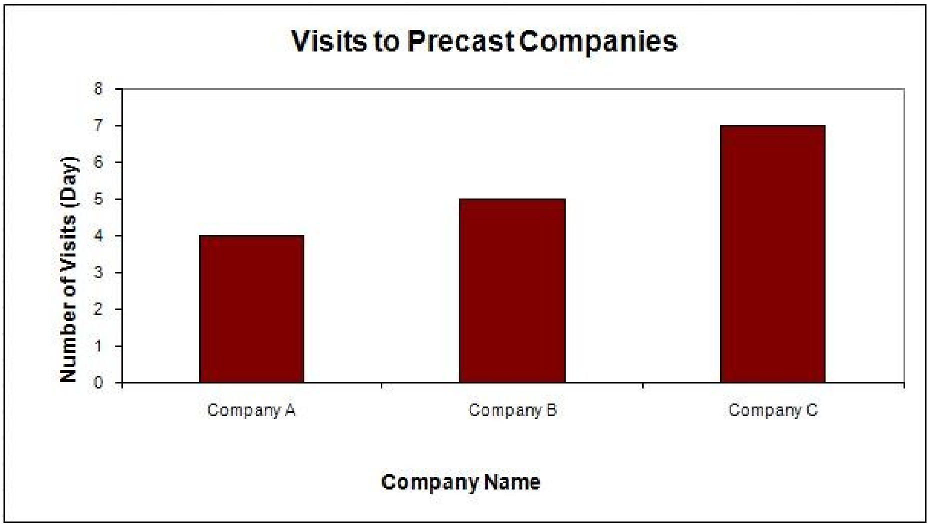


Figure 3.5: Site visits made for each company

Figure 3.5 shows that four visits were made for the first precast company, five visits were conducted at the second company, and seven visits were made to the third one. A range of different skilled personnel were interviewed, the skill levels ranged from operator to technical manager. See figure 3.6

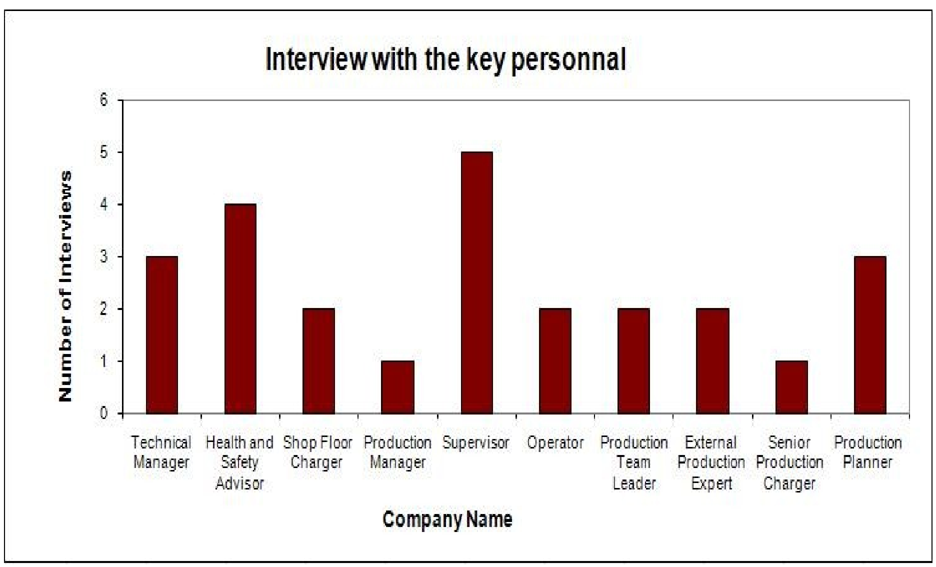


Figure 3.6: Interview key personnel in the precast industry

In figure 3.6, a number of technical managers working across three precast companies were interviewed three times. Other personnel including operators, shop floor chargehands and supervisors were met to gain knowledge about the logic of processes and other technical issues. The number of hours spent at each of the three companies is shown in figure 3.7.

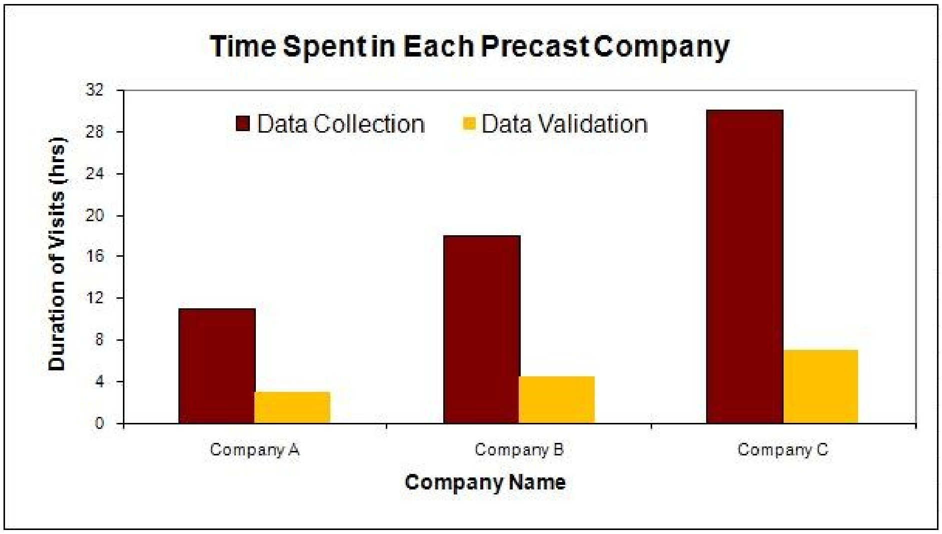


Figure 3.7: Number of hours spent at each company

The spent time at each company was divided between data and logic collection with validation of the collected data at a later stage. Although, company B was visited five times, only one working shift was considered during each visit.

However, company C (the sleeper producer) had two working shifts which enabled a larger number of visits to take place. After applying this methodology, a generic process map of the business including manufacturing processes was developed. The development of process map of each company provided the required scope for the development of a generic process map for the precast manufacturing system using batch manufacturing processes.

In the next subsection, generic process maps using IDEF0 are discussed in detail.

3.4.1.1 Process Mapping

IDEF0 visual modelling diagrams were developed for a generic precast concrete labour-intensive manufacturing system; the first IDEF0 describes the top level of the business structure with the business processes. This IDEF0 diagram was developed after considering three business processes elicited by the researcher after a number of visits to the three companies (see *appendix F*). Business process maps were used to indicate the organisation of the top level functions and to show the logical relations amongst those processes. Validation feedback was utilised after completing a process, to update previous processes, see figure 3.8 for the general business process map of a batch concrete manufacturing system.

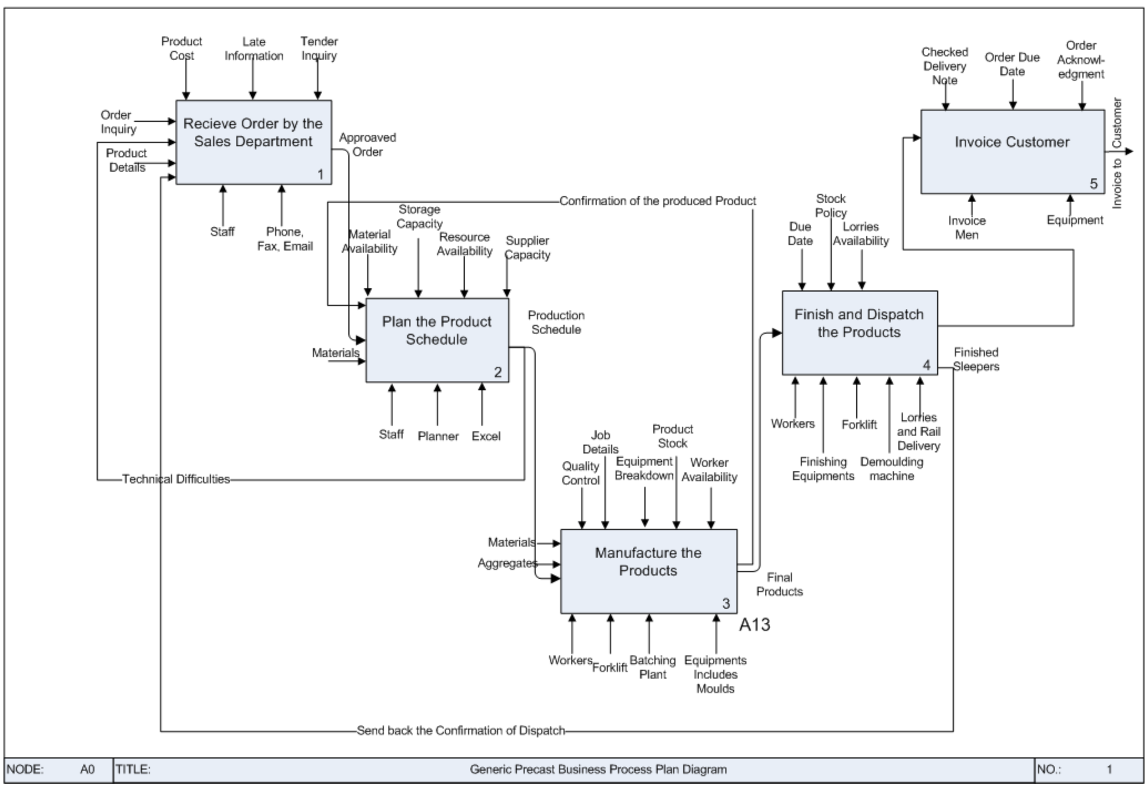


Figure 3.8: High-level business process mapping diagram

The flow comprised five major business processes, which were summarised as: order receipt, plan and schedule; manufacture products, finishing and dispatching precast products and finally invoicing customers. Each process involved a set of activities and a series of these activities formed the detailed business system of the company. The first stage in the planning process being order receiving, in which the sales department was responsible for receiving orders, specifying required product details, and providing the product batch size (quantity and type of products to be produced). The second stage: being to plan the production schedule in which products to be produced. Excel was used by the scheduler to produce the production schedule. A confirmation was then sent back to the sales department which was responsible for indicating if there were any technical difficulties or insufficient material quantities. The third stage which this study focused on was the manufacturing process. This process involves the activities carried out in the shop floor, the supervisors receiving the production plan/schedule being responsible for carrying out the production operations, according to the specified plan. A number of factors that affecting the progress of the manufacturing system were identified including: worker availability, machine breakdown, mould-availability, etc. A confirmation/acceptance was provided to the scheduling department, for further updates.

In the fourth stage, the finishing works were conducted to finalise batch production processes before dispatching; forklifts were used to move the finished concrete products from the shop floor to the open stockyard area. Lorries and trains were used to transport orders to their final destination. A dispatch confirmation was sent back to update the orders and sales department on the status of the order being produced. The last stage was the fifth stage, in this stage, invoices were sent to the customers to confirm the delivery of the placed orders once they were ready for delivery from the stockyard.

The precast concrete manufacturing system consists of one or more production section (only two production sections are described in this study). The first one (known in the plant as section 1) was used to produce different types of products while production section 2 was used to produce only one type of batch concrete products.

A process map was developed to show the factors influencing the decision on which production section was to be responsible for the product processes and relevant activities. This type of detailed process map assisted the scheduler to decide the sequencing and labour and materials requirements, etc.

The developed IDEF0 model enabled the simulation analyst to understand all of the complex activities involved in the manufacturing systems associated with this type of industry. Only the detailed manufacturing process was involved in developing the crew allocation system. Three process maps were developed to indicate the different production strategies to be applied in a number of precast companies, see *appendix G*.

A generic production strategy applicable to two precast concrete production sections was developed. See figure 3.9

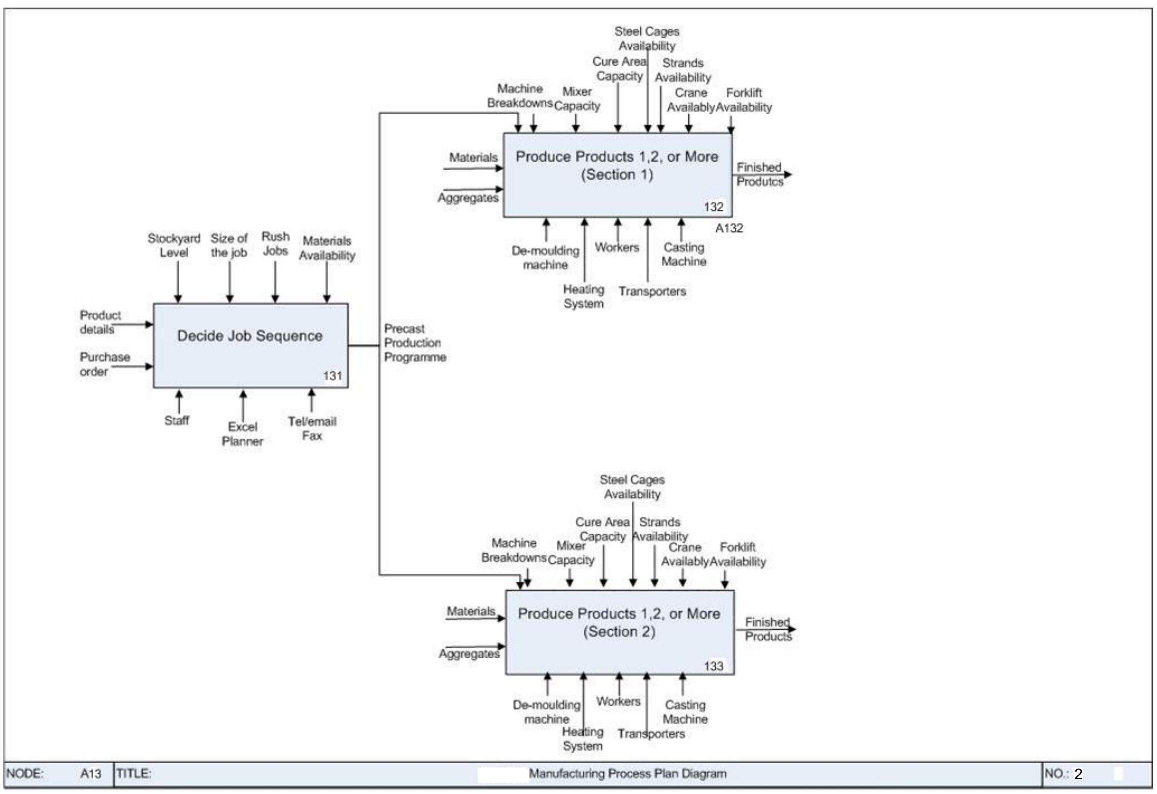


Figure 3.9: IDEF0 diagram for the precast concrete production planning in two production sections

In figure 3.9, the process map shows the factors that affect the decision process of starting a job in any of the production sections. All processes in the two production sections were mapped to identify inputs, resources; constraints affecting each process, and the resulting outputs of each process. One or more product types were capable of being produced in both production sections. Similar/different products were produced in both production sections.

This type of visual modelling identified all of the circumstances that affect the production processes. Nine generic processes were mapped to gain a full understanding of the production life cycle at each production section. A generic manufacturing processes map was developed following consideration of other process maps for a number of precast companies (see *appendix H*). Figures, 3.10 and 3.11 show IDEF0 diagrams concerning the manufacturing phases.

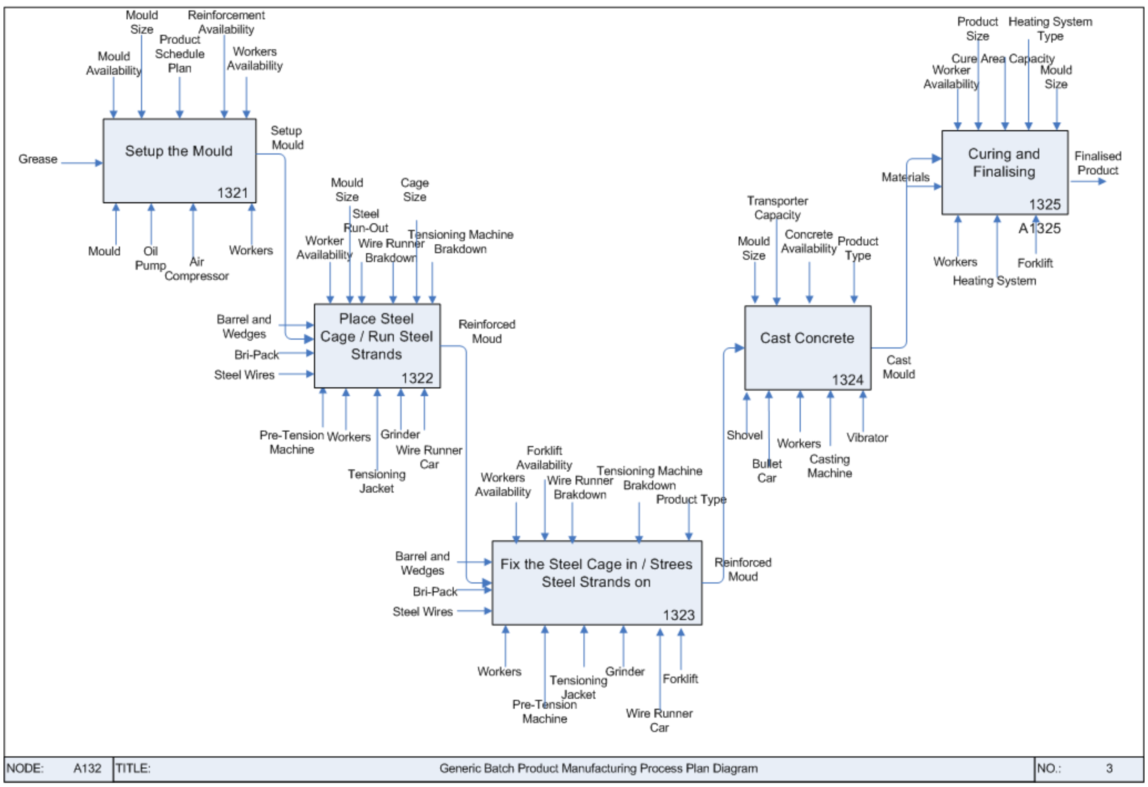


Figure 3.10: Generic process mapping diagram of precast concrete manufacturing

In figure 3.10, the first process to produce the batch concrete product is the setup process. In this process, all inputs, restrictions affecting the setup process and resources used to carry out this process, and outputs were defined. Run steel strand or place a steel cage into a mould (depending on the product type) was the second process followed by, stressing the strands or fix the steel cage into the mould. The casting process was then applied after the strands had been stressed or placed inside the mould.

The fifth process was referred to as the curing and finalising the batch concrete product. This process involved five generic sub-processes and it was not possible to include all of them in process map 3.10. These processes were analysed and modelled in a separate process map. See figure 3.11

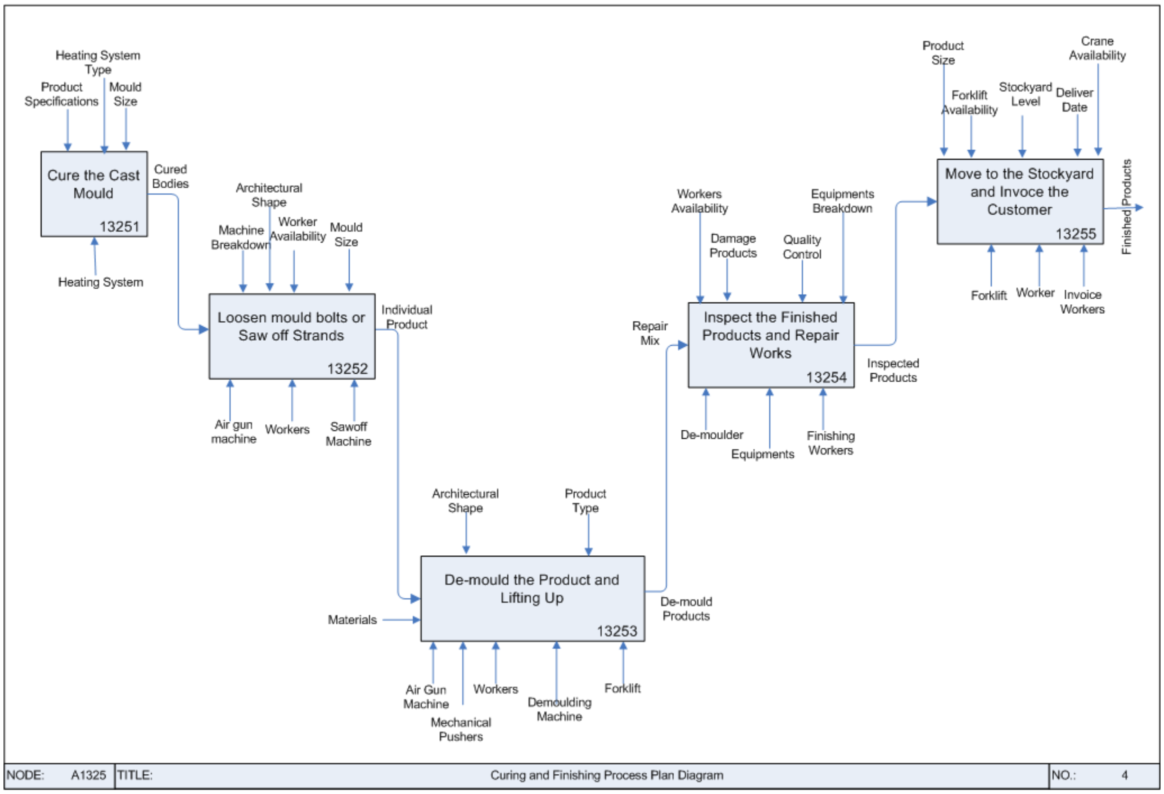


Figure 3.11: Casting and finalising process mapping diagram

In figure 3.11, the process flow starts from the curing process in which a steam blanket system was used to cure the cast concrete body. The curing area capacity and availability of plastic sheets was the restriction of the curing process. Demoulding followed the curing process. This involved the following processes: loosen mould bolts or cut off the strands and then demoulding the concrete products with a special demoulding machine.

Finishing of the products was a necessary process which compromised the activity of placing plastic rubber clips on each unit. Moving of the products to the stockyard was the last process.

All inputs, outputs, constraints and resources regarding each process were defined to gain knowledge of the core of each process and how these processes were related to each other.

3.4.1.2 Flowcharting

Flowcharts were developed to describe processes at a detailed level. A flowchart is defined as a pictorial representation describing a process being studied or even used to plan stages of a project (Arzola, 2006).

In this subsection, a flowchart was used as a tool to break down the logic of each production process into individual activities. Then each activity was referenced to its time duration to acquire process details. Flowcharts of each production process beside a number of snapshots was captured to formulate the effective visual tools, alongside other data collection tools (see *appendices H and J*). The flowchart tool was selected to improve understanding of the production processes. The flowcharting approach used, provided a means of comprehensively documenting and evaluating a wide spectrum of business process controls (Reding et. al, 1998). After developing and producing all the required process logic, development of the simulation model is discussed in detail in the following subsection:

3.5. DEVELOPMENT OF SIMULATION MODEL

3.5.1 The Modified Decomposition Algorithm

In this section, a modified decomposition simulation methodology was presented in order to develop the simulation model. In this methodology, after problem definition, the problem is decomposed into a number of sub-problems in order to facilitate investigation, modelling and analysis of each sub-problem. After which a simulation process of each sub-problem was required, to produce sub-models. Each sub-problem was then verified to check whether or not the modelling process logic of the sub-problem was conducted correctly. If not, then the simulation process was reviewed and compared with the logic of the sub-problem. After verifying each sub-model, a validation process takes place to ensure that the simulated sub-model accurately represented the real problem. A verification process was utilised to ensure that simulation sub-model produced precise outputs. The simulation methodology addressed by Banks, (1999) was modified to enable the modelling of larger scale problems. See figure 3.12

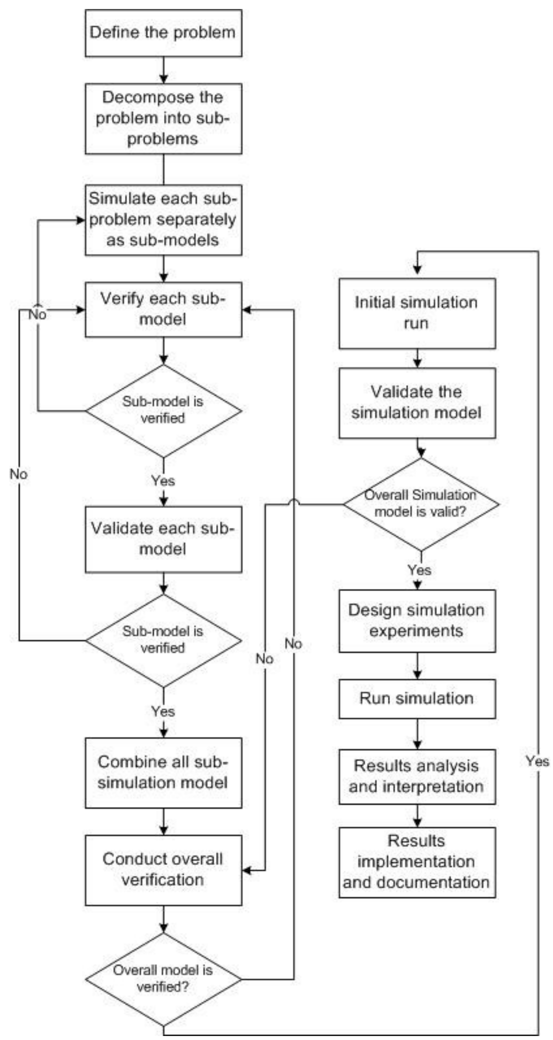


Figure 3.12: The modified decomposition simulation methodology, (modified from Banks, 1999)

After verification and validation of each sub-model had taken place, all simulated sub-problems were combined together to form the whole simulation model. A thorough verification and validation process was used to check on whether or not the combined sub-models reflected the real world. If not then each sub-model was reviewed again.

Simulation experiments then designed to be run before by executing the simulation model. All results were analysed and interpreted before documenting them. The Architecture of the simulation model was necessary to identify the structure of the simulation being modelled.

3.5.2 Architecture of the Precast Labour-Intensive Simulation Model

After the simulation methodology had been chosen, logic addressed in the manufacturing process maps (IDEF0 diagrams) was used to develop the architecture of the simulation model. The architecture showed how the current simulation model is working in terms of integration with a database. See figure 3.13 for the high level architecture of the simulation model.

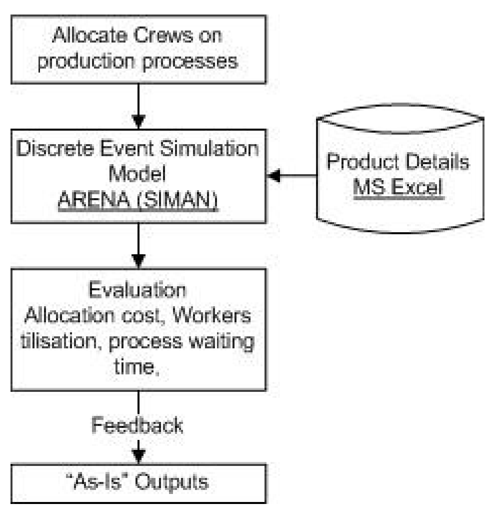


Figure 3.13: Architecture of the simulation model

The developed architecture shows an Excel database which was integrated with the developed simulation model in order to provide it with the required production information. Each crew of workers was assigned to be fed manually into each process module as no automation was possible before any integration with an optimisation module took place. After entering all data, a simulation run was useful to evaluate the current allocation plan in terms of a number of performance criteria including allocation cost, process-waiting time and worker utilisation (discussed in chapter 6, section 8).

3.5.3 Construction of Labour-Intensive Simulation Model

For modelling simplification purposes, the manufacturing system being investigated was divided into two zones: '*batch plant zone*' and '*production processes zone*'. A sub-model of each zone was then developed to imitate all processes carried out at each zone.

After developing the sub-models, integration was employed to form the required simulation model. The developed simulation model was then decomposed into two sub-models:

- Batch plant (Mixer process)
- Production processes

These sub-models led to the modelling processes being simpler and more flexible:

- Sub-Model 1: Modelling of the Mixer Process

The logic of the mixer operation was identified by developing a process flowchart. This flowchart provided information on how the mixer works.

To simulate mixer operations, related information was taken into consideration including: the required concrete needed to produce a product, status of the mould and other related technical information.

A specific flowchart was designed to track the technical requirements. The logic of the batch plant operation was developed and shown below in figure 3.14

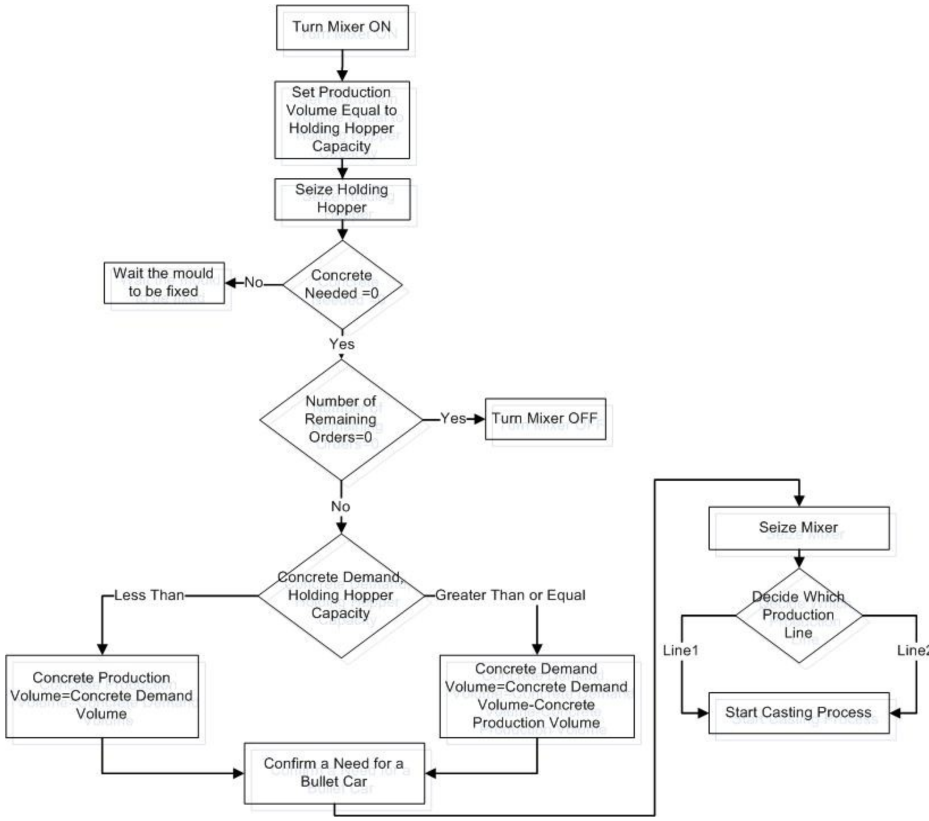


Figure 3.14: Logic of the mixer operations

In the batch plant logic presented in figure 3.14, variables were used to model any required quantities of concrete and to calculate the total satisfied demand for concrete at any time. Logical statements executed different procedures depending on the resulting value of a variable. The number of orders was modelled as a variable; a zero value of this variable being enough to decide the termination of the mixer operation.

- Sub-Model 2: Modelling of the Production Processes

Simulation modelling of one production line consisting of eight production processes was investigated in detail to provide a view of the simulation logic of such processes.

The first module was designated as the "SEIZE" module which was used to seize all orders to be processed on First Come First Served (FCFS) basis when a mould was available.

A series of production processes were carried out to obtain the required order ready for dispatch to an open stockyard. The set-up process was modelled as the first module which consisted of resources (labour plus machines) and process time. After set-up the mould, the run of strand process was modelled, as the second module, a set of workers' associated with the wire runner car to be used to run the strand in the mould was modelled. A press stress process was then modelled, in a module in which a 'set of workers' and a 'stress machine' with a specified process time was included. The casting process was then applied on the mould, to fill it with the required amount of concrete, as the fifth module. A curing process was applied on the cast mould to ensure that the concrete was cured; no resources were used with the exception of the energy associated with the steam generator. A sawing process was then applied to the cast concrete to split each product for further processes followed by demoulding and finishing processes.

Figure 3.15 describes the production process operations

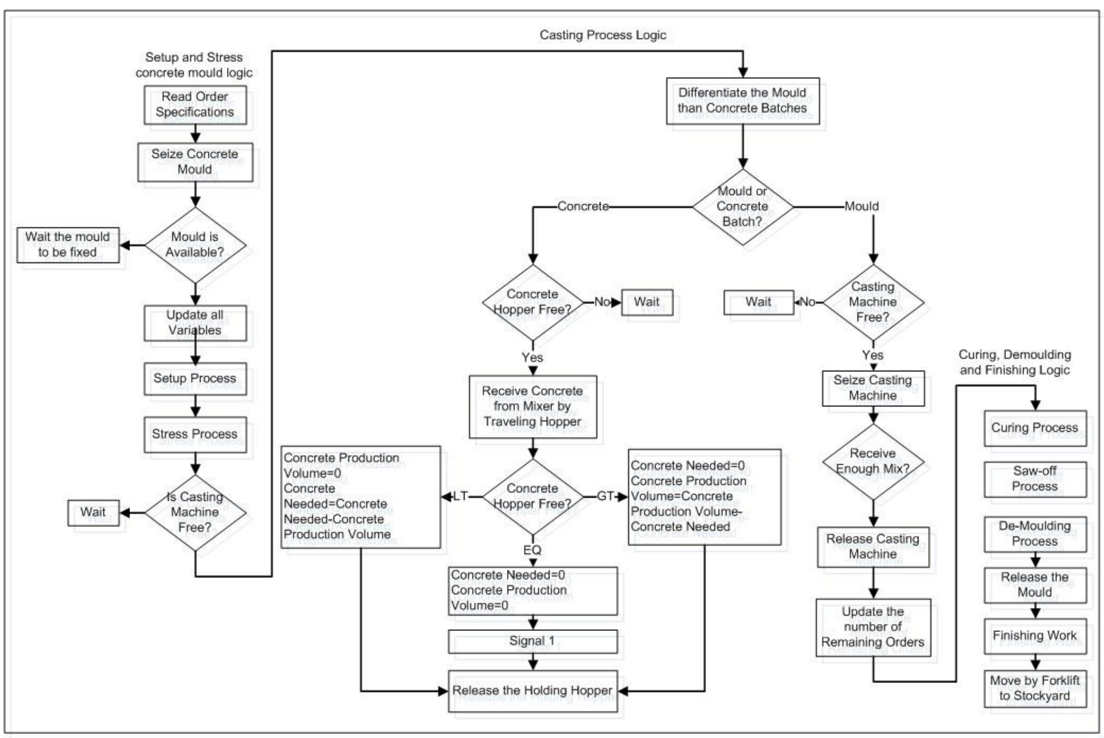


Figure 3.15: Logic of the production process operations

All logical relationships needed to simulate the production zone are shown in the developed flowchart above. In figure 3.15, each production section was simulated with basic animation introduced for each of them. Two production sections are sharing the same mixer to provide concrete for each, when needed, and were simulated accordingly.

In the next section, the development of the optimisation module is discussed in detail. This optimisation module was designed to be embedded into the simulation model to improve its searching capability in order to gain more promising solutions.

3.6 DEVELOPMENT OF OPTIMISATION MODULE

3.6.1 Multi-Layer Genetic Algorithm

After developing the simulation module and in order to generate and test more allocation plans, an optimisation module was developed, to be integrated with the simulation model. Genetic Algorithms were selected as the optimisation module for the allocation problem being solved, due to its capability to deal with a population of solutions (see chapter 2, section 2.3.7 for the reasons of selecting GA as optimisation search engine). A GA is defined as a computational model simulating the process of genetic selection and natural elimination in biological evolution (Kumar, et. al, 2009).

The benefit of using Genetic Algorithms within simulation models is to refine the search for an optimum or near-optimal solution. The combination of simulation and optimisation can be defined as the process of finding the best set of input variables without evaluating each possibility (Molnár, 2004). It is difficult to find satisfactory solutions for real-life allocation problems requiring a substantial amount of computations, using a traditional GA approach. In previous works, multi-layer GA models were developed either in terms of multi-level GA's in which each level is a separate traditional GA (Kelareva and Negnevitsky 2001) or by dividing a traditional GA model into several layers, each layer representing a part of the initial problem

(Negnevitsky and Kelareva 2008). Both studies above used a traditional chromosome (vector) in the problem formulation.

In this study, the proposed multi-layer Genetic Algorithms model is different to other research attempts in that it provides more flexibility for dealing with multi-attributed inputs, and the ability to solve crew allocation problems in a parallel-repetitive processes layout. The proposed chromosome structure used alongside developing GA operators and adoption of the "non-repeatability" condition was necessary to differentiate the developed model. Aforementioned modifications enabled the proposed GA model to have a more organised input processing capability than other traditional models (in the traditional models, genes are encoded by a vector representation called a chromosome).

In the proposed Multi-Layer GA algorithm, a Multi-Layer initial population (initial day and night crew indices for each process) was generated using Monte Carlo (MC) sampling techniques as a starting solution; decimal coding was applied to suit crew index number (1,…n) where n is number of crew alternatives available for each process.

Then, Genetic Algorithm started with repeating the genetic cycle of manipulating chromosomes, from initial random population of chromosomes to generate new generations consisting of "fit" offspring. During this process, each individual was evaluated using the simulation engine: the resulting simulation can be thought of as a mechanism that turns input parameters to output performance measures (Law and Kelton, 1991). The evaluation criterion was the objective function.

At the end of each generation, all objective function outputs required sorting in an ascending order; those with minimum costs being kept on the top of the selection list for further selection. If the convergence condition was satisfied, then the required results were enough to terminate the GA loops. See figure 3.16 shows the proposed algorithm of Multi-Layer Genetic Algorithms.

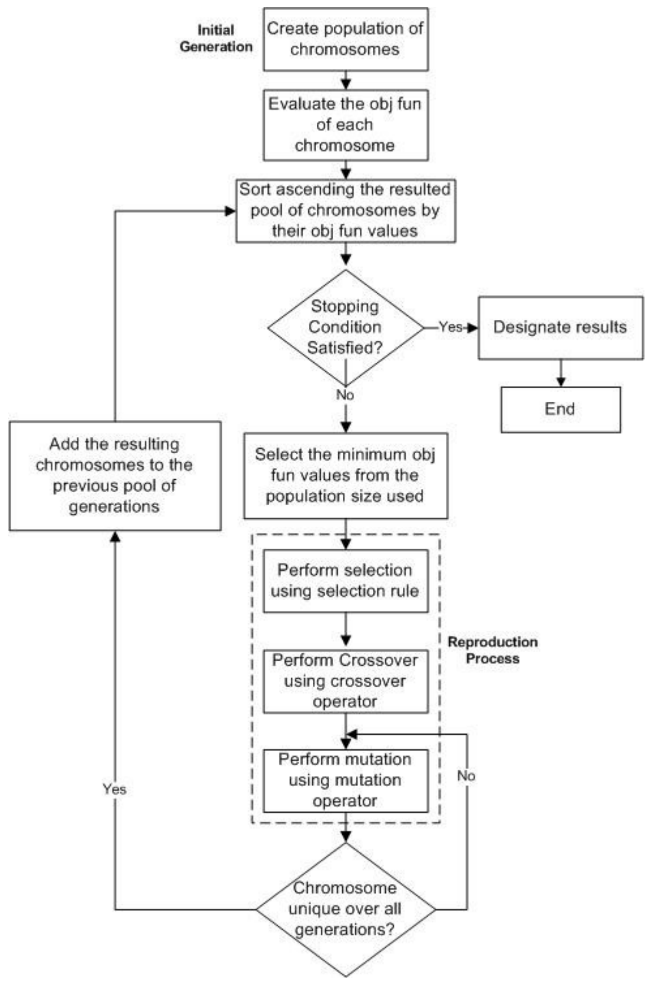


Figure 3.16: The Multi-Layer GA flowchart

For further computations, the reproduction process was started by identifying a list of chromosomes with minimum allocation costs. This list was placed on the top of the selection list for further investigation. A proposed selection rule, to decide which pair of significant chromosomes had to be selected for further investigations, was required.

The extended description of the GA mechanism in figure 3.16 was used to demonstrate the means of testing only unique (non-repeated) chromosomes. In addition, it was shown that mutation operator can play a vital rule in achieving that uniqueness besides adding more randomness to the searching process.

A “Class-Interval” selection rule was developed (see section 3, section 6.1.3). The idea of this selection rule was inspired from the “class-interval” concept used to tabulate a set of observations in the descriptive statistics. The proposed selection rule was developed to provide a better chance for promising chromosomes (with minimum costs) to be selected as pairs. The selected pair of chromosomes was then subjected to a ‘Probabilistic Dynamic Crossover’ operator in which an exchanging of some genes takes place between different chromosome layers. To avoid un-matured solutions, another operator called ‘Probabilistic Dynamic Mutation’ was applied on the crossed-over pairs of chromosome. The purpose of applying such an operator was to add more randomness whilst exploring solutions through multi-layer space and to provide a unique chromosome.

In the developed algorithm, the Probabilistic Dynamic Mutation operator played a vital role in randomising the searching process. The last step in this algorithm was updating all generations with the resultant outputs, selecting minimum cost outputs for further reproduction process.

In the next section, A Uni-Layer chromosome is presented to provide an idea about how decision variables in terms of crews are placed and arranged to for a chromosome.

3.6.1.1 Uni-Layer Crew Allocation Chromosome Engineering

The purpose of developing a Uni-Layer chromosome structure was to deliver the idea of modelling simple one-shift crew allocation problems in a simple way. The chromosome structure was designed to be able to accommodate efficiently, a set of data having the same attribute, such as a 24 hours working shift. This traditional chromosome was flexible and simple crew allocation problems were easy to model. Figure 3.17 shows the Uni-Layer chromosome structure for simple crew allocation purpose.

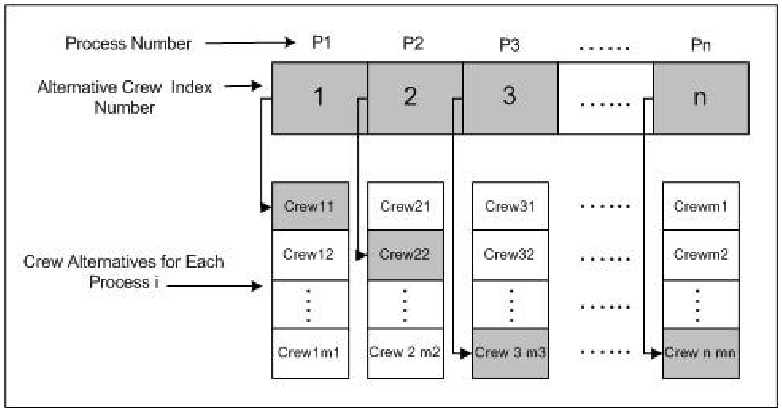


Figure 3.17: Chromosome representation for crew allocation problem

In figure 3.17, each integer number of each gene provides the crew index number of the set of crew alternatives associated with that gene. i.e, this number gave the index of a crew to be used in the solution. Each gene has different possible alternatives of crews to be used in the solution. It was found that decimal methodology was most appropriate to model crew indicies. The chromosome length representing the maximum number of processes involved in the labour-driven production facility.

Manufacturing systems in most labour-intensive industries adopt more than one working shift. The limitation of the uni-layer chromsome is that one layer in the designed chromosome was not enough to accommodate more that one set of inputs having different attributes. To overcome this limitation and to add more flexibility to a uni-layer chromosome, a Multi-Layer chromosome was designed to be a promising accomodation for such multi-attributed sets of inputs. This flexibility enabled a chromsome to store different sets of inputs in more than one layer. The modelling of a multi-shifts crew allocation system was the driver for developing a Multi-Layer chromosome structure idea.

3.6.1.2 Multi-Layer Crew Allocation Chromosome Engineering

The design and structure of any chromosome depends on the problem requirements. In a Multi-Layer chromosome, each layer can be used to store a set of inputs; each set of inputs has to contain a particular attribute. This design is efficient, when more than one set of inputs, having different attributes for each set is available. In this chromosome, the content of each gene was represented by a crew for a certain process at a specified shift.

The number of genes was equal to the number of processes and number of layers was equal to the number of attributes (shift type, process priority…etc).

A column vector was attached with each gene as an available crew alternatives pool; each pool of each process had a different number of alternatives (minimum labour requirement is satisfied for each process) as it depended on the nature of process and the availability of crews. The decision variables were placed in a row vector (string) called a chromosome. This chromosome consisted of a number of elements (genes) representing the number of variables. The Multi-Layer chromosome structure was proposed to provide more flexibility and to have less parameter to pass, to enable easy comparison. See figure 3.18 for the Multi-Layer chromosome structure

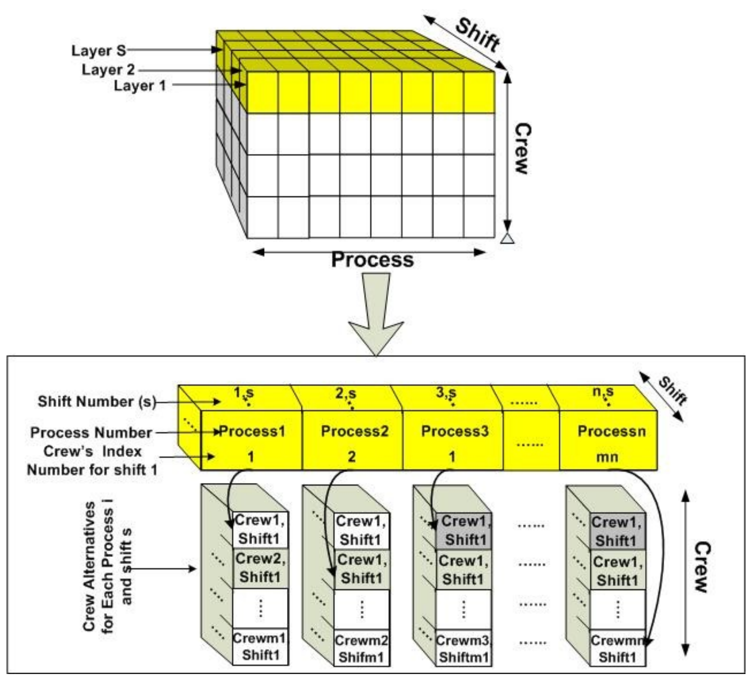


Figure 3.18: Mutli-Layers chromosome structure

The idea behind the designing of a Multi-Layer chromosome structure was to indicate how different sets of inputs can be stored in a chromosomal structure design. This structure was used to present all sets of inputs in more than one layer so that it could be coded more easily and provide improved presentation later.

A multitude of attributes of sets of inputs in such a problem chromosome can be designed, in such a manner. For each process, possible alternatives of crews were stored into a pool of crew alternatives. The first layer of the chromosome involved all possible daytime shift crews to be assigned to daytime processes. The second chromosome layer was assigned to accommodate the possible crews of night time shift workers. Each gene at each layer was used to accommodate possible crews of workers which can be called from the crew pool in the developed Access database.

The current design of chromosome enables Sequential Query Language (SQL) to guide the searching mechanism for any process to find a possible crew of workers in an efficient way, and it is possible to have one or more shift of work activity. Each process may involve more than one crew of workers in which any of them is able to carry out a process with different crew formation and within a particular processing time. Jobs of each process can be carried out using more than one working shift to satisfy clients commitments, thus not all processes necessarily have the same number of working shifts.

The developed Multi-Layer chromosome enabled each set of data with the same attribute to be placed into its layer. As an example, in a manufacturing system with 12 production processes, 8 of the processes work just a day shift while 4 processes need a night shift as an overtime requirement. This sort of flexibility is feasible using the developed chromosome structure.

- **Objective Function of Crew Allocation System**

The purpose of allocating crews in an optimal way was to improve system performance; thus, system performance parameters such as: throughput time, process waiting time, resource utilisation and allocation cost obtained from running the simulation were used to develop the fitness value within the GA operation.

The objective function was applied to evaluate the total allocation costs. The equation used to calculate such objective function was:

$$f(x_i) = \sum_{i=1}^{m} BRC_i + IRC_i + RCPU_i \qquad \text{…. (3.1)}$$

Where:

BRC_i incurred cost per hour when using a labourer for set of solution i.

IRC_i incurred cost per hour when labourer is idle for set of solution i

$RCPU_i$ incurred cost per use of mould or physical resource for set of solution i, senior skilled bonus can be considered in such cost.

This cost information was identified from previous job-shop cost records. The difference between RCPUi and BRCi is that the first cost incurred per use of a fixed resource (mould) or physical resources (machines) whilst BRC can only be incurred when there is a work rate i.e worker per hour. Two types of costs were defined in the objective function: the incurred cost when the resource is busy and the other when the resource is idle. The idle time caused by waiting for a complete crew of workers can cause additional costs. In some situations, there is a trade-off between idle time and cost (El-Rayes and Moselhi, 2001). In this study, only direct cost was considered as a substantial cost.

- **Calculation of Fitness Function**

One of the most difficult tasks in creating the genetic algorithm was the correct design of the objective function. This function being responsible for evaluating the quality of a given code string. For minimisation type problems, minimum costs were required to be selected in order to improve the solution towards achieving global minima. As cost values were minimised, the GA required the value of the objective function to be non-negative, the modified objective function is called the fitness function i.e.

$$Gx_i = Max - f(x_i) \qquad \text{…. (3.2)}$$

Where:

Gx_i : fitness function value for chromosome i

Max : largest cost in generation i

$f(x_i)$: cost objective function value by evaluating chromosome i

3.6.1.3 Multi-Layer Genetic Algorithm Operators

- **The Developed Class Interval Selection Rule (CISR)**

In the selection process, the fitness information was used to adjust the survival probability of each member of population; then probabilities were used to randomly select survivals. In this selection rule, only the promising chromosomes with least costs or higher fitness functions were considered as a potential improvement vehicle. The selection rule dubbed "Class Interval" rule was developed to provide the promising chromosomes with higher probability of selection to produce good solutions.

The main concept of this selection rule depends on constructing a "Class Interval" structure which is used commonly in descriptive statistics (Healey, 2009). Repetition of any generated chromosome was not allowed as a '*One Search*' strategy (explained in chapter 7, section 3.5) and was developed to avoid any duplication, so all generated chromosomes were unique throughout the evolution process. Then the relative fitness function RGx_i was calculated using the following formula:

$$RGx_i = \frac{Gx_i}{\sum_{i=1}^{m} Gx_i} \qquad , \text{i=1,..} m \qquad \text{…. (3.3)}$$

Where:

RGx_i : Relative fitness function of chromosome i

m : Population size

A cumulative relative fitness function was then calculated as it was used to determine the desired class width as in the following formula:

$$CRGx_i = CRGx_{i-1} + RGx_i \qquad , i > 1 \qquad \ldots. (3.4)$$

Where:

$CRGx_1 = RGx_1$

RGx_i : Relative fitness function of chromosome i

$CRGx_i$: Cumulative Relative fitness function of chromosome i

Then, the possible interval of occurance for each chromosome was determined in terms of class intervals. The interval associated for each chromosome represented the chance range of that chromosome being selected by any (0-1) random variate. See figure 3.19

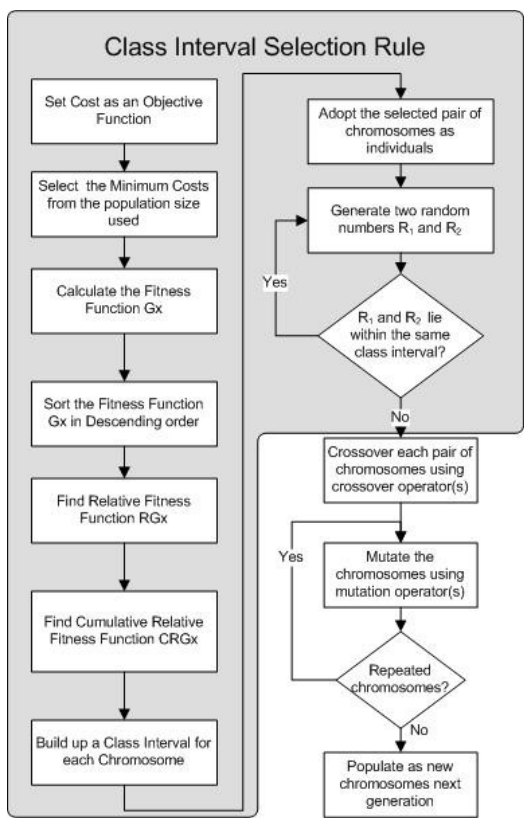


Figure 3.19: The proposed Class Interval (CI) selection rule

Then, a possible interval of occurance for each chromosome was determined in terms of class intervals. The interval associated with each chromosome represents the chance range of that chromosome being selected by any (0-1) generated random variate. A number of operators were designed to add more randomness whilst searching for solutions. These operators are discussed in detail as follows:

- **Probabilistic Dynamic Crossover (PDC) Operator**

The crossover operation in a conventional GA is based on the exchange of genes between two fixed length chromosomes when coding was applied for chromosomes. In order to crossover genes in the chromosome, (0-1) variates were generated for each gene in the multi-layer chromosome. This type of exploration investigated all active genes (occupied genes by scheduled crew with a shift) for more randomness.

A random number was then generated to exchange genes after satisfying a certain condition. In this strategy, random numbers were generated to be attached for each gene at each layer, if the gene was vacant for any reason then the generated random number was discarded to skip to the next gene. The suggested probability was the crossover of the gene rather than enabling the crossover of a chromosome.

In this type of crossover, n random numbers were generated to be associated with each gene, a vertical crossover taking place to swap or alternate subsequently n gene(s) of the first chromosome with the opposite gene of the second selected chromosome after satisfying the condition: *If probability of crossing over a gene ≤ random number associated with that gene then crossing over of that gene is possible.* PDC was developed to achieve the best random exchanging of genes between each pair of chromosomes, see figure 3.20

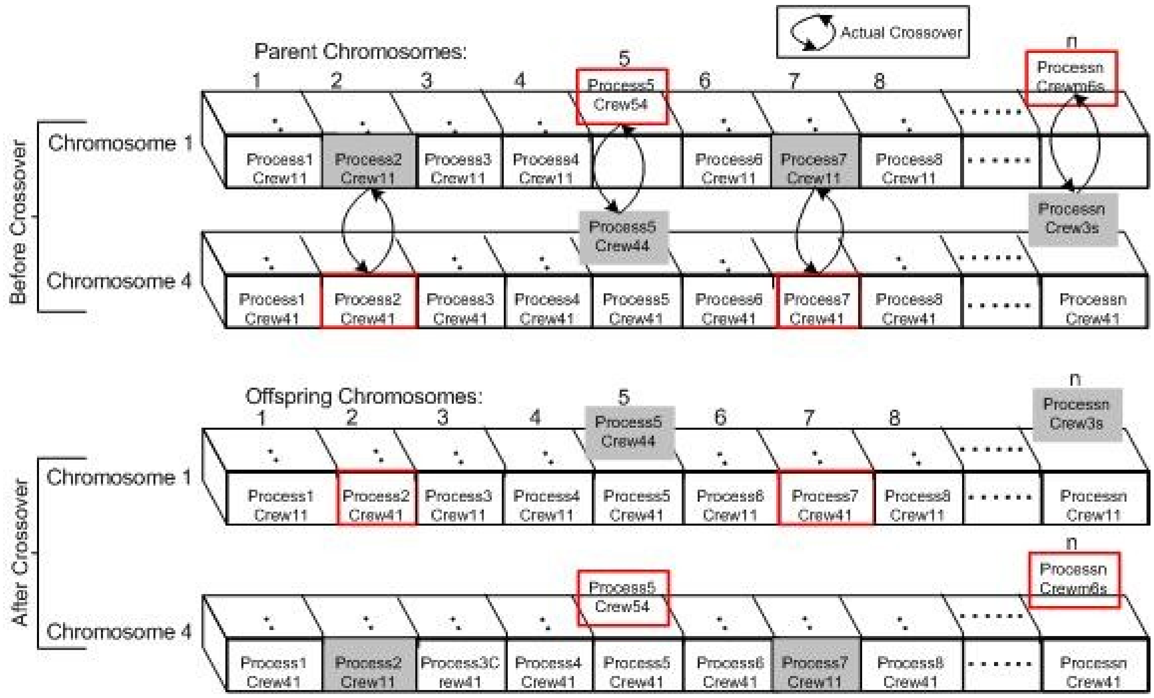


Figure 3.20: Multi-Layer Probabilistic Dynamic Crossover Strategy

The (0-1) generated random numbers were designed to be associated with each gene at each dimension, a random number was discarded when a gene was vacant (no shift applied to a crew). The probability of crossing-over a gene decided whether that gene could be swapped with the opposite chromosomes' gene or not. For example, suppose the four random numbers satisfies the swapping condition at genes 2, layer1, 5, layer3, 7, layer1 and n, layer6. The chosen places or genes would be vertically exchanged for each selected pair of chromosomes.

This type of crossover strategy can provide an equal chance for all genes to be exchanged with the opposite chromosome's genes. In this strategy, any repeated chromosomes were discarded as the mutation operator keeps exchanging genes till a unique chromosome was found. Genes selection by cost can be applied, lower cost achieved priority for selection (Kotecha et. al, 2004).

- **Probabilistic Dynamic Mutation (PDM) Strategy**

To avoid local maxima and to randomise the searching process, a modified mutation process was developed to swap the gene within a chromosome with its available set of alternatives. In this strategy, (0-1) random variates were generated to be associated with each gene of the chromosome; random variates for vacant genes were discarded. The forms of crossover operators and mutation operators also depended on the way the problem was coded, (Leu and Yang 1999). Monte Carlo (MC) sampling was then applied to search stochastically for a crew within each assigned pool of crews. See figure 3.21

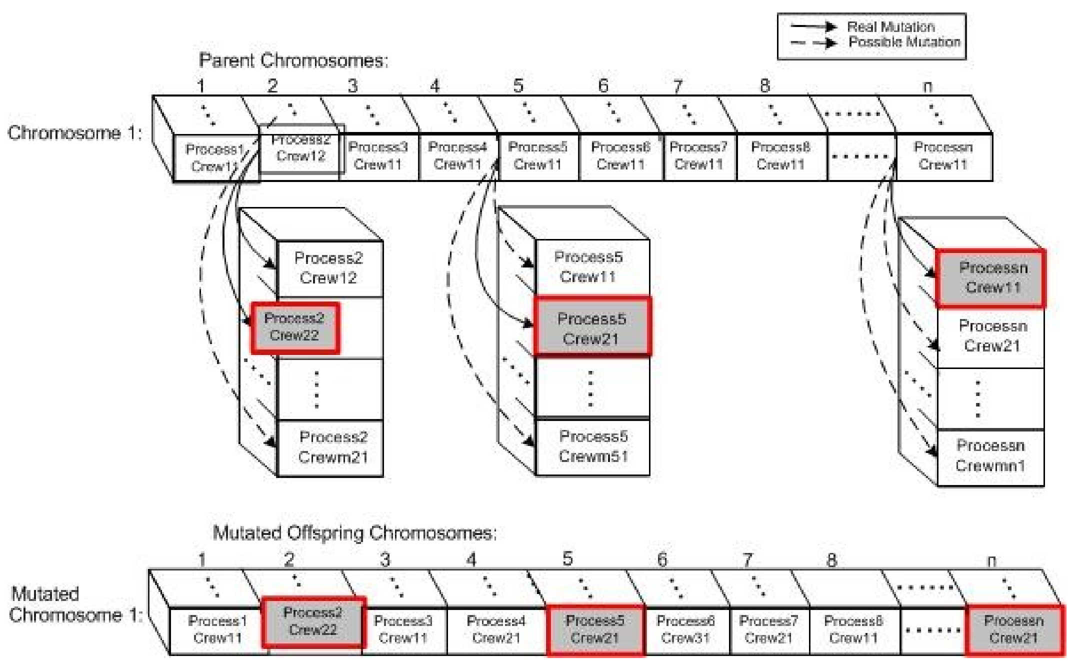


Figure 3.21: Multi-Layer Probabilistic Dynamic Mutation Strategy

In this type of mutation, each offspring (an individual chromosome) was randomly selected and various genes mutated vertically with its set of alternatives from the multi-layered pool of crews' alternatives.

- **Stopping Criterion**

Several approaches can be used to stop a sequence of successive population generations depending on the form of the response surface, the quality of the desired optimal solution, and the assigned computation time. As a common criterion to stop a GA, the convergence to a point where all generations become alike was selected. In the current developed methodology, a stopping criterion was adopted to stop the algorithm when no considerable cost improvement was found after a number of consecutive generations. (Five generations were adopted in this study).

3.7 CHAPTER SUMMARY

In this chapter, the conceptual model was developed to identify inputs, process, and outputs of the proposed allocation system. The development process of the 'SIM_Crew' system was illustrated in terms of IDEF0 diagrams. Three main processes were discussed in detail to reflect the development process. A methodology to develop the model specification was introduced and data collection techniques were discussed. The data collection process was discussed in detail. Process maps were developed to reflect the logic of the precast manufacturing system. The architecture of the crew allocation system was then developed and discussed and simulation methodology was presented alongside the process logic required to simulate the production process was demonstrated. The development of the Genetic Algorithms model was discussed and the modifications in the chromosome structure, selection rule and other operators were addressed.

This chapter effectively established the specifications and framework for developing a prototype for a crew allocation system, which will be used to develop the allocation system in the next chapters.

CHAPTER 4

LABOUR-INTENSIVE MANUFACTURING SYSTEMS: THE SLEEPER PRECAST CONCRETE PRODUCTION FACILITY

4.1 INTRODUCTION

In this chapter, the sleeper precast concrete manufacturing company is considered as a case study. An adequate amount of the collected information and the developed logic of processes was the motivation to select it from other cases. In this case study, multi-production sections can be seen in a job-shop environment in order to produce a range of precast products. Each production section has a number of similar/different production processes which require shared skilled workers. Due to the multi-production section layout available in such systems, one or more process may require the same worker to carry out jobs. This problem results in a high allocation cost and this problem has to be solved to guarantee the best flow of work. However, the purpose of developing such a case study is to capture the required logic, system layout, and data to solve such problem in the precast labour intensive system.

4.2 DATA COLLECTION METHODOLOGY

The following tools were selected and used as the methodology in collecting data:

4.2.1 Site Visits

In order to collect the required amount of information (process logic and resource process time) for the proposed allocation system, four visit days were conducted. These visits were divided into day and night visits in order to capture the process flow and to identify the production life cycle at each working shift, see figure 4.1 for more details about the site visits.

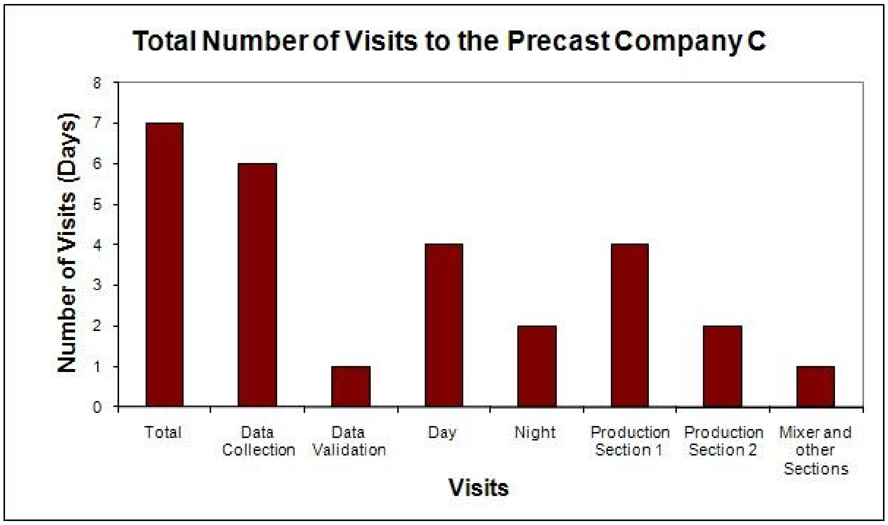


Figure 4.1: Total number of visits to the precast company

Six days were spent collecting data and one day visit for data and output validation. The day time visits were overlapped with the night shift to enable the process logic to be captured. Production section 1 was visited four times with two visits for section 2.

However, the logic of processes and all relationships was found to be similar in both sections, the only difference is that each production system had a different process time and worker information. The Mixing and other production sections were visited to establish the links with other resources available in other manufacturing sections. During the site visits, a number of structured interviews were conducted to collect the required amount of information.

4.2.2 Structured Interviews

The structured interview technique approach was chosen in order to collect the required data and a data collection instrument was designed in the form of document containing a number of questions divided into three categories. These categories: identified the problem, data collection, and suggested improvements and solutions. Sixteen personnel from four precast manufacturing companies were interviewed and the chart indicating the responses and actions taken is shown in *appendix K*.

The following figure shows the range of personnel who were selected to give a balanced view:

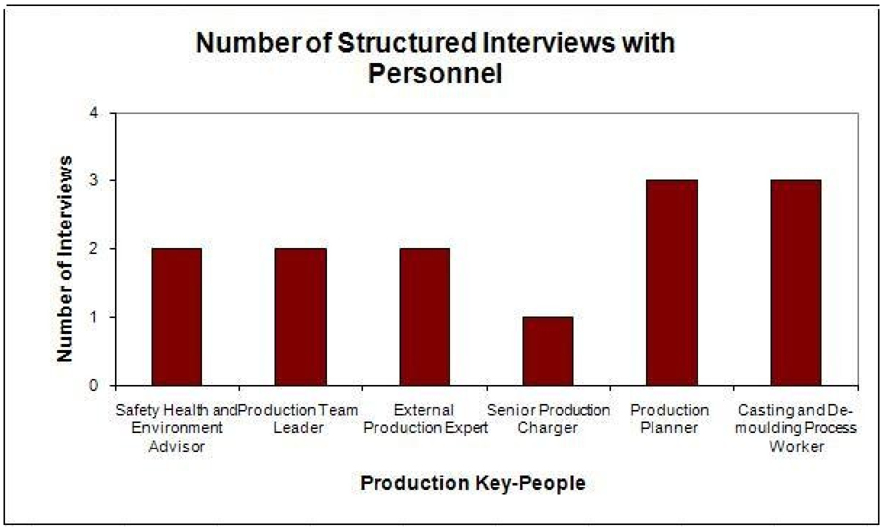


Figure 4.2: Number of structured interviews with personnel

Fourteen questions were carefully designed to extract specific information from the skilled people involved in the precast manufacturing process. The questions were developed to identify the problem and to collect the relevant data. Full co-operation from the workforce was essential to identify the true logic involved in the processes and collect the required amount of data.

Two interviews were conducted with the Safety Health and Environment (SHE) advisor in order to understand health and safety regulations applied in the precast company. The production team leader was interviewed twice to capture an overall view of the manufacturing system. An external production expert who had worked for more than 30 years in the precast concrete production section (retired) was approached and took part in the structured interview procedure.

The required level of information, all logical relationships between process and the process detail at each production section were obtained during thes interviewes. The senior production chargehand was interviewed to understand the logic of a number of production processes. The production planner was interviewed three times, two times to capture the required information and to identify the current and alternative skills matrix of crew of workers and one to validate the collected data and other system outputs. The casting and demoulding workers were interviewed three times to collect the required amount of information and to capture the logic of the production processes.

The structured interviews were designed starting with more general questions about the manufacturing system and relationship between production processes and then more detailed questions, regarding process details, were addressed to senior chargehands (a senior chargehand is the high-skilled worker responsible for the flow of work) at each production section.

The production planner was encouraged to participate in suggesting solutions for the current allocation problem. The idea of improving the current allocation plan was started by introducing the concept of simulation to the production planner in order to test a number of the existing allocation plans. The idea was developed further to investigate all the possible allocation plans. The 'Genetic Algorithms' Concept was introduced, at a later stage of development. The answers to the questions through a number of structured interviews resulted in a precise understanding of the crew allocation problem, behind the high production cost. In addition, the logic of all production processes and other relevant data was collected and documented in the form of process maps and flowcharts.

The structured interview times were varied depending on the skills and the amount of knowledge which the personnal had. See figure 4.3 for the interview times.

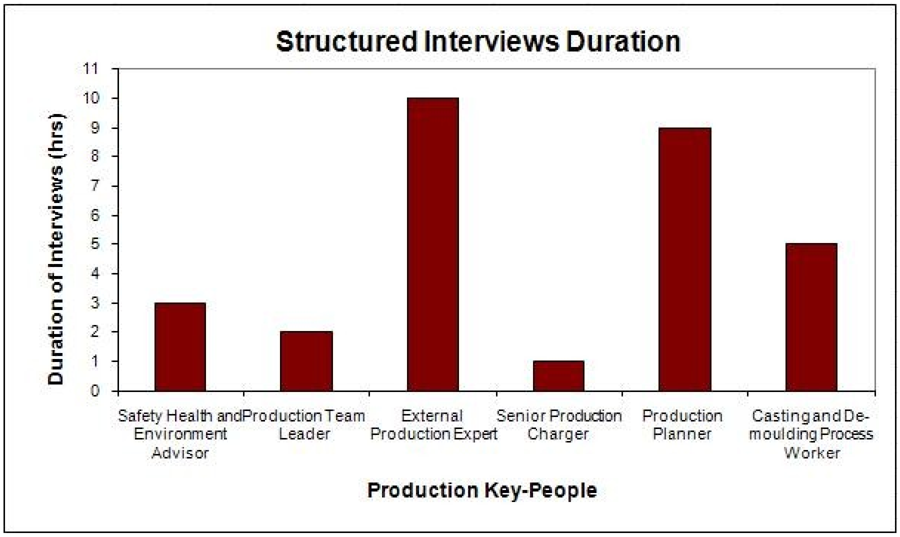


Figure 4.3: Structured interviews duration

Figure 4.3 shows that three hours was spent with the SHE adviser to understand the health and safety regulation applied in the company. Two hours were spent to capture the required logic and other relavant information through asking the production team leader a number of questions. Ten hours were spent interviewing the external production expert, the discussion was focused on the logic of each production system. This interview resulted in capturing an overall understanding of the manufacturing system and other process details. A one hour interview was conducted with the senior production charger to collect a number of process logic details. A nine hours interview with the production planner was fruitful in collecting the logic of the production processes and to validate the collected data alongside other outputs. The five hours spent with the casting and demoulding workers was enough to collect the required information regarding casting, demoulding and finishing processes. A four hour meeting with the production planner was enough to form and provide the skills matrix and other alternatives required by each process. The rest of the skill matrices required especially for production section 2 was sent via the personnel e-mail of the production planner. The casting and demoulding worker (mutli-skilled workers) provided the technical information about the production processes in each production section.

4.3 TYPES OF COLLECTED DATA

- Inputs

In order to develop the simulation model, the required data were categorised as follow:

- Order specifications: involving the type of the product, the quantity needed, process and other setup times, the amount of materials required for each order and fixed resource status (available or not)
- Labour information: including the skills matrix required for each process, alternative crews possible for each process, crew efficiency in terms of process time, hourly cost depend on skills, shift type (day, night).
- Logic of the processes and other related relationships.
- Process restrictions and the resources.

4.4 DESCRIPTION OF THE MANUFACTURING SYSTEM: PRODUCTION LAYOUT

In the sleeper manufacturing system, a wide range of different shared resources, including workers, equipment and materials are utilised. The sleeper concrete manufacturing system is divided into two main production sections. Each production section has two labour-driven production lines. Shared resources are used at each production section. Eight production processes including the curing process are applied on each production line. In any of the production lines, a "reusable mould" is the main resource. This consists of a gang of moulds that can be used to produce either the same or different types of sleeper.

To increase knowledge and understanding about the labour-intensive manufacturing system, a schematic diagram presented in figure 4.4 was developed to show an overall picture of how system components were arranged to give the required flow of work.

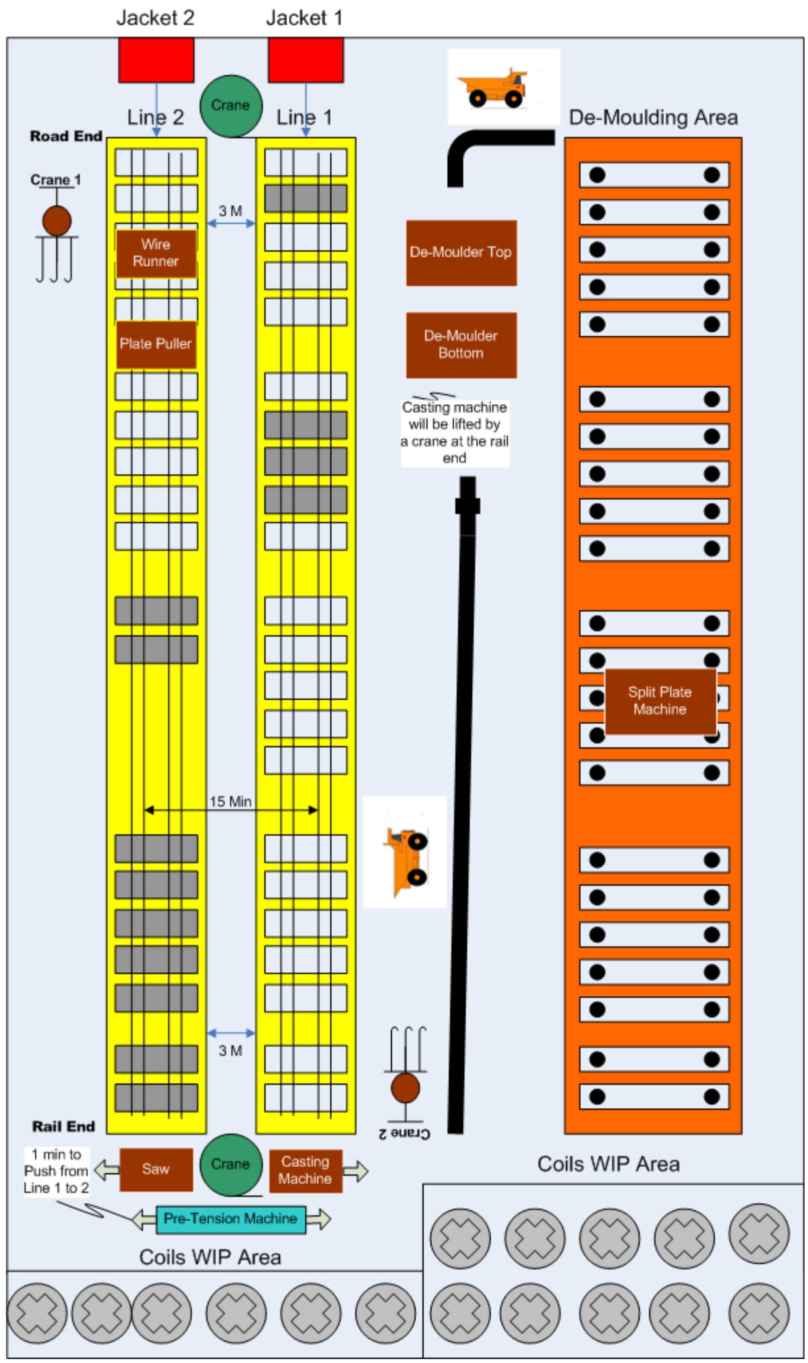


Figure 4.4: The schematic diagram of a sleeper's production section

Figure 4.4 shows a number of shared physical resources which can be used in each sleeper production line. These resources are operated by a number of skilled workers. Table 4.1 shows the used physical resources in production section 1. These physical resources can be located in WIP area after utilisation.

Table 4.1: The set of physical resources used in production section 1

Process	Resource
Setup	Mould, oil pump, air compressor
Run steel strand	Wire runner car, grinder, tensioning jacket
Stress	Pre-tension machine, tensioning jacket, grinder
Cast	Bullet car, casting machine
Cure	Heating system
Saw	Sawoff machine
Demould	Demoulder
Finish	Finishing tools

Only heavy resources involve casting and demoulding machines are shared between two production lines within the same production section. Pushers and cranes are used to move the shared resource to the desired line.

4.4.1 Existing Production Processes

As mentioned earlier, the sleeper precast concrete system consists of two production sections. The first one (known as section 1) was used to produce different types of sleepers while production section 2 was used to produce only one type of sleeper (G44).

The process flow starts from the mould set-up process where the inputs of this process are grease and pandrols and other related materials. The restrictions imposed on this process are mould, labour availability and the schedule programme. The resources required to carry out a set-up process were: an air compressor, moulds, labourers and other related resources. The second process was to place strands inside the mould so that the sleepers could be reinforced, a third process involved stressing of a varying number of strands depending on the type of sleeper. After this process, the casting process was applied to fill the moulds with the required amount of concrete. The curing process was the fourth process in which a steam blanket system was used to cure the cast sleepers.

The curing area capacity and availability of plastic sheets was the restriction of the curing process. Demoulding followed the curing process. This involved: cutting off the strands and then demoulding the sleepers with a special demoulder machine. The finishing of the sleepers was the last process which compromised of placing plastic rubber clips on each sleeper.

4.4.2 Product Variety: Snapshots

The manufacturing system in the company was specialised in producing sleeper products. A “sleeper” is a rectangle precast component for use as a base for railway tracks. Sleeper components are generally laid transverse to the rails, on which the rails are supported and fixed, to transfer the loads from rails to the ballast and sub grade below, and to hold the rails to the correct gauge. Different types of sleeper products are produced in two production sections. A number of special sleeper products G44, 5F40, 5EF28, EG47, and EG473R were produced in production section 1 while only G44 type was produced in production section 2. See figure 4.5 for different sleeper products

Figure 4.5: Types of sleeper products

4.5 ALLOCATION OF THE MANPOWER

Two types of multi-skilled workers were used to carry out jobs in the sleeper manufacturing system: Chargehands (multi-skilled workers in charge of operators) and operators (multi-skilled workers). Each multi-skilled worker had enough skill to carry out a number of possible activities. This number depended on the accumulated skills of the worker and his/her ability to work on more than one process.

In production section 1, eleven operators and two chargehands were used to carry out jobs during the day shift. Ten operators and two chargehands were used to carry out jobs during the night shift, which were left over from the day shift. In production section 2, thirteen operators and four chargehands were used in one shift. The current available skilled workers (chargehands and operators) in the sleeper manufacturing system are presented in table 4.2.

Table 4.2: The available workforce for the sleeper job-shop

Section ID	Chargehand ID		Operator ID		Section ID	Charge-hand ID	Operator ID
	Day Shift	Night Shift	Day Shift	Night Shift		Day Shift	Day Shift
Production Section 1	w05	Nw02	w01	Nw01	Production Section 2	w14	w15
	w06	Nw04	w02	Nw03		w18	w16
			w03	Nw05		w22	w17
			w04	Nw06		w26	w19
			w07	Nw07			w20
			w08	Nw08			w21
			w09	Nw09			w23
			w10	Nw10			w24
			w11	Nw11			w25
			w12	Nw12			w27
			w13				w28
							w29
							w30

Both Chargehand operator categories were identified by the production planner according to the accumulated experience record of a worker. The crew alternatives for each production process were provided by the production manager as in table 4.3

Table 4.3: Number of crew alternatives for each process

Section ID	Line ID	Process ID	Number of Crew Alternatives	Section ID	Line ID	Process ID	Number of Crew Alternatives
Production Section 1	Production Line 1	Setup	4	Production Section 2	Production Line	Setup	3
		Run Strand	4			Run Strand	3
		Stress	4			Stress	3
		Casting	4			Casting	3
		Sawoff	3			Sawoff	3
		Demoulding	4			Demoulding	3
		Finishing	4			Finishing	3
	Production Line 2	Setup	4		Production Line	Setup	3
		Run Strand	4			Run Strand	3
		Stress	4			Stress	3
		Casting	4			Casting	3
		Sawoff	3			Sawoff	3
		Demoulding	4			Demoulding	3
		Finishing	4			Finishing	3

According to the above table, the possible number of allocation plan equates to 722204136.308736 possible plans which indicated that the crew allocation problem to investigate was a combinatorial complex one. More details about crew formation data and worker skills are confidential and cannot be published in this thesis.

4.5.1 Working Shift System: Simple Chart

Because different types of sleeper were produced, two working shifts were adopted in production section 1. The first shift starting at 5:00AM ending at 2:30PM known as the day shift and 5:00PM till 3:00AM known as the nightshift. In production section 1 the day shift strated with the setup process,which was then followed by run strand, and stress, ending with the casting process. The sawoff process was then achieved during the nightshift, followed by other production processes before the day shift returned. See figure 4.6 for the working shift plan in production section 1

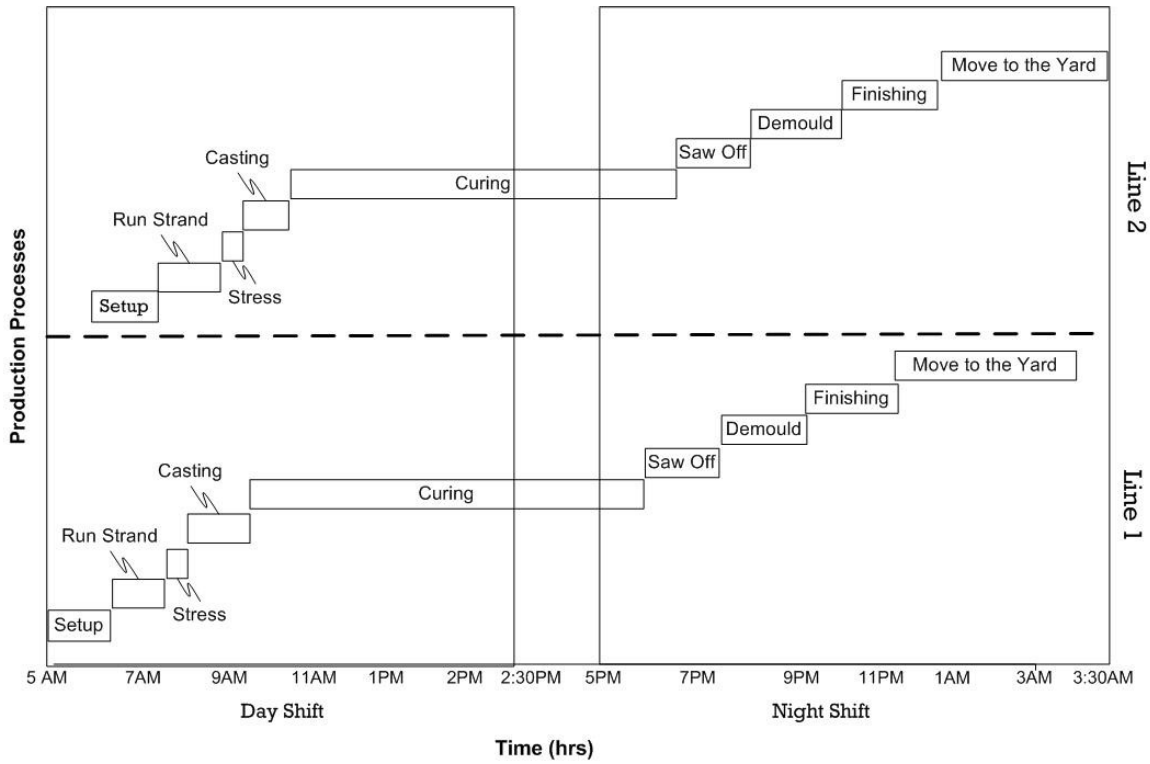


Figure 4.6: Two shifts of working in a precast manufacturing system

Production section 2 adopted one working shift as this section was used to produce one type of sleeper product. The adopted day shift in this production section started with the setup process and was followed by run strand and stress, ending witht the finishing process. The mould being cured was left overnight before demoulding process took place during the following morning. See figure 4.7 for day shift applied in production section 2

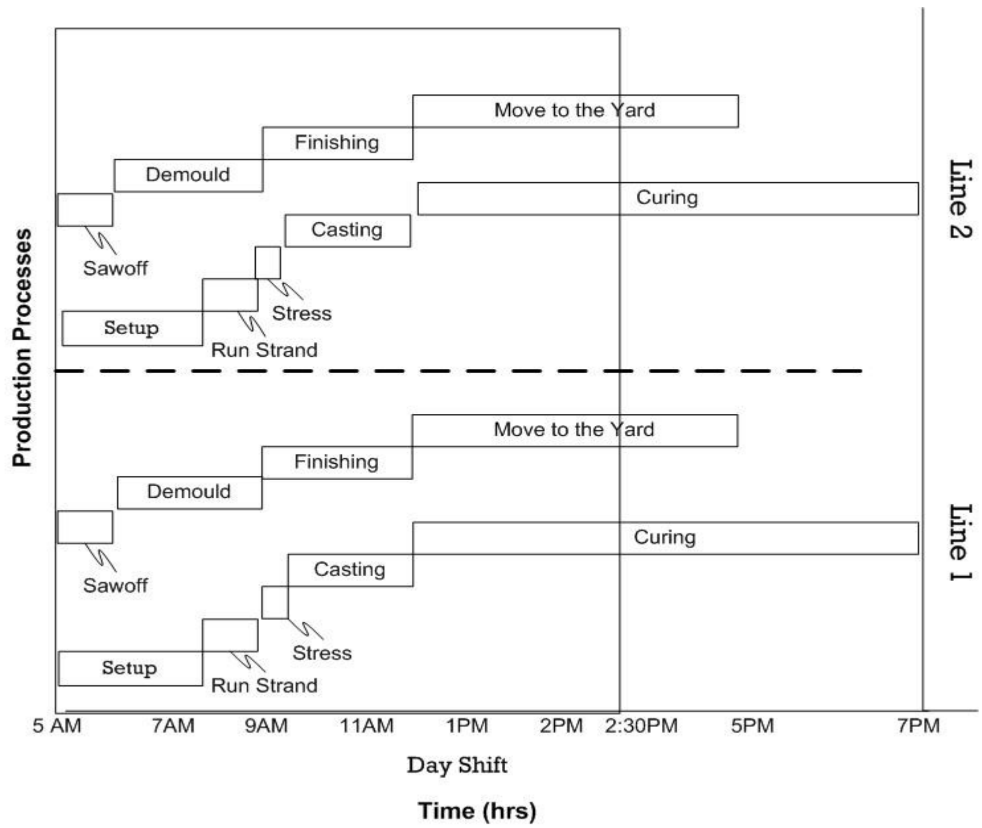


Figure 4.7: One shift of working is adopted in one of the sleeper production sections

The individual product life cycle applied in two shifts of working can be represented in terms of a flow diagram. See figure 4.8 for two shifts flow diagram for a particular production line.

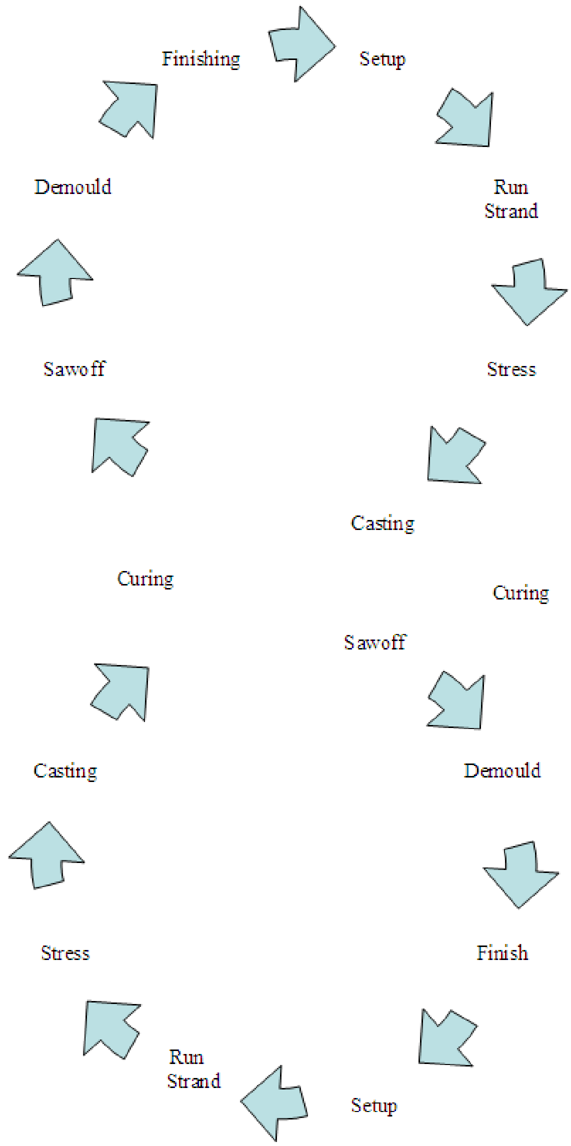


Figure 4.8: Day and nightshifts within a production cycle at production section 1

The day shift started with a setup process and ended with a curing process while the second working shift continues with sawing-off products and then setting up the mould again ending by casting process to be delivered to the next shift crews of workers. The alternate shift system is shown in more detail in table 4.4

Table 4.4: The schedule of crew to be working on two production lines of production section 1

Day	Shift	Day Activities	Night Activities
Mon	Day	Cast	Sawoff→ Demould→ Setup→Run Strand→Stress→Cast
	Night	Sawoff→ Demould→ Setup→Run Strand→Stress→Cast	Sawoff→ Demould→ Setup→Run Strand→Stress
Tue	Day	Sawoff→ Demould→ Setup→Run Strand→Stress→Cast	Cast
	Night	Sawoff→ Demould→ Setup→Run Strand→Stress	Sawoff→ Demould→ Setup→Run Strand→Stress→Cast
Wed	Day	Cast	Sawoff→ Demould→ Setup→Run Strand→Stress→Cast
	Night	Sawoff→ Demould→ Setup→Run Strand→Stress→Cast	Sawoff→ Demould→ Setup→Run Strand→Stress
Thr	Day	Sawoff→ Demould→ Setup→Run Strand→Stress→Cast	Cast
	Night	Sawoff→ Demould→ Setup→Run Strand→Stress	Sawoff→ Demould→ Setup→Run Strand→Stress→Cast
Fri	Day	Cast	Sawoff→ Demould→ Setup→Run Strand→Stress→Cast
	Night	Sawoff→ Demould→ Setup→Run Strand→Stress→Cast	Sawoff→ Demould→ Setup→Run Strand→Stress

In the above table, the working schedule of processes in two production lines of section 1 is illustrated. During each shift, different crews of workers were assigned to carry out jobs. In table 4.4, starting from Friday night, the operations of: setup, run strand, stress, and casting processes were carried out on the first mould, and then the work pattern moves on the second mould, casting process cannot be carried out in the same shift due to the limitation of the shift duration. The next morning, the cured mould has to be sawn off and demoulded to be prepared for casting after carrying out setup and other preparation steps.

Each day, in a particular day shift at least one mould should be ready to be filled by concrete, while the other moulds are prepared to be sawn off and demoulded, ending up with three moulds ready to receive concrete. See table 4.5 for the schedule of crew to be working on two production lines of production section 2.

Table 4.5: The schedule of crew to be working on two production lines of production section 2

Day	Shift	Day Activities	Night Activities
Mon	Day	Cast	Sawoff→ Demould→ Setup→Run Strand→Stress
Tue	Day	Sawoff→ Demould→ Setup→Run Strand→Stress→Cast	Cast
Wed	Day	Sawoff→ Demould→ Setup→Run Strand→Stress	Sawoff→ Demould→ Setup→Run Strand→Stress→Cast
Thr	Day	Cast	Sawoff→ Demould→ Setup→Run Strand→Stress→Cast
Fri	Day	Sawoff→ Demould→ Setup→Run Strand→Stress	Sawoff→ Demould→ Setup→Run Strand→Stress→Cast

In table 4.5, the mould at production line 1 was assumed to be prepared since late of Friday's day shift. Then work is started to cast line 1 and prepare line two to be casted next day. This alternative sequence is continued for the rest of the week days. See figure 4.9 for the work life cycle in the mentioned section.

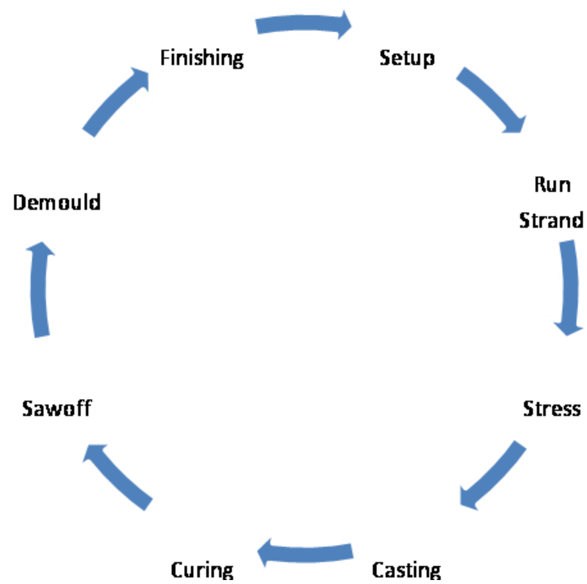


Figure 4.9: Day shift of production cycle at production section 2

In the production life cycle above, the setup process started as the first process on first mould; run strand and stress processes are performed on the same mould, the casting process starts after placing and stressing strands to receive concrete. On the same day, after casting the first mould, processes are swapped to the second mould, to repeat the same activities. After filling two moulds with concrete, both of them were left overnight. On the second day: sawoff, demoulding, finishing processes were applied on both moulds in turn, and then setup, run, stress and casting processes was carried out on the same day on both moulds respectively. The production capacity of section 1 and 2 is (2×6) and (1×6) sleeper moulds per production cycle. The considered production cycle was 6 days and 19 hours. The daily production capacity for section 1 and 2 were (1×2) and 1 mould respectively.

It was noted that the production capacity of section 1 was greater than section 2 as two shifts were adopted in the first section while only one was applied on the second section. It is difficult to identify the production capacity of each line as the production process in such sections is alternatively conducted for each production cycle.

4.6 PROBLEMS IDENTIFIED

There is an increasing cost in the sleeper production sections due to the improper labour management. The improper allocation of crews of workers between each two production lines of each section results in high process-waiting time. In addition, increasing process-waiting time can result in significant delay by increased labour idle time and subsequently affects the overall allocation cost. The production manager uses a spreadsheet application to manage the crew allocation task. Using such an application cannot consider the effects of other factors such as utilisation and other waiting times. In addition, testing more than one alternative is time consuming using a spreadsheet application. The production planner was only able to produce initial allocation plans without optimisation.

4.7 CHAPTER SUMMARY

In this chapter, the sleeper precast concrete production facility was presented as a labour-intensive manufacturing system. Data collection methodology was developed in order to collect the required information about the manufacturing system being investigated. The precast manufacturing system in terms of its layout was described in detail. The allocation of manpower in such industry was explained and a shift working system was described in simplified charts. The problem of allocating crews to processes was identified in this chapter. This chapter was used in order to provide the required information about the sleeper manufacturing system for further modelling.

In the next chapter, databases are designed to store and retrieve the collected data.

CHAPTER 5

MODELLING OF LABOUR MANAGEMENT DATABASE PHYSICAL MODEL

5.1 INTRODUCTION

The development process of a labour resource allocation system requires databases to store and retrieve labour information when needed. The storage and retrieval processes in an efficient way, eventually aids production planners to achieve more intuitive interpretation of data rather than just viewing what has been deposited.

The purpose of designing such a labour information database was to facilitate information exchange between both the simulation model and the optimisation engine. This type of labour information exchanging can assist both the simulation and genetic algorithms models in terms of evaluating/generating one or more possible allocation plans.

In this chapter, databases for labour resources allocation requirements are developed to input all labour relevant data, enabling data viewing in a flexible manner, and to search data by querying the developed database. All of the labour data was collected using the process described in chapter 4. The developed labour information database can be described as a labour inventory tracking system. However, these databases were developed to store information concerning labour information, and production specifications and retrieve them when needed. In addition, the outputs from the optimisation process in terms of possible allocation plans can be stored in the database for further analysis.

5.2 STRUCTURE OF ‘SIM_CREW’ DATABASE

The human resource allocation system ‘SIM_Crew’ was designed to be integrated with several different databases. This integration was necessary to retrieve inputs and generate outputs while evolving solutions. Many databases were integrated with the allocation systems, some of them were used to provide the simulation model with the required inputs, and others were used to support the optimisation engine with the required information, Dawood[2] and Marasini (2001). For verification purposes, other files were used to accommodate the resulted optimisation outputs. Different components (simulator and optimiser) could then be integrated together via a database to enable data interchanging process between them, Katalinic, et. al (2001). See figure 5.1 for the integration of databases with other allocation engine components.

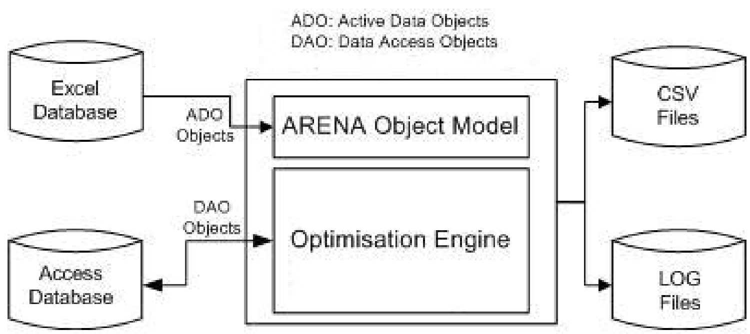


Figure 5.1: Structure of ‘SIM_Crew’ Database

The structure of the ‘SIM_Crew’ database consists of several databases that have integrated with the allocation system via Microsoft Integration Technologies. Some of those databases were used to provide inputs and host the evolved outputs for further evaluation. Other databases were LOG and Comma Separated Value(s) CSV files, which were, developed to prove the validation of the proposed allocation system.

The crew allocation process needs to access data from different data sources. This access was achieved using different data exchange technology, which depended on the type of database. Data Access Objects (DAOs) technology was used as an abstraction to access data sources stored in the Access database. This sort of integration technology encapsulated the underlying storage mechanism, managed connections to store, and query data by exposing the interface to a business component.

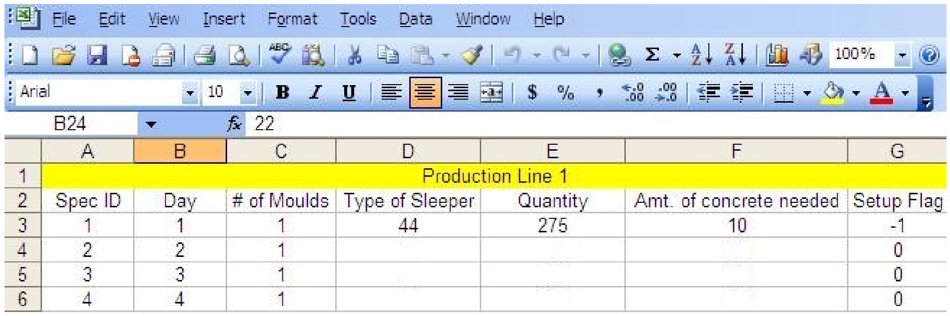
In figure 5.1, the databases can be accessed via Data Access Objects (DAO) or ActiveX Data Objects (ADO); both of them being Microsoft Integration Technologies. These objects represent the structure of the database and the data it contained. With the database integration, the simulation output was written back to the developed database. In addition, the generated and evaluated possible crew allocation plans were stored back into the Access database in order to generate more possible crew allocation plans for further comparison.

Two databases were developed in order to assist the crew allocation process in terms of storing production and labour information. The next subsection will describe each database in detail:

5.2.1 Development of Production Information Database

An Excel database was developed to provide the allocation system with the required production information needed by the simulation model to execute the simulated labour-intensive manufacturing model. The collected production information described in chapter 4 is stored in the developed database. The purpose of developing this database was to provide the simulation model with the required production information that enabled the simulation to be run as an allocation plan evaluator. The developed database consisted of production information including number of available moulds, types of the products required to be produced, quantity of concrete needed to produce a certain amount of products and other flags (useful for programming and simulation purposes).

See figure 5.2 for a snapshot of production information database



Production Line 1						
Spec ID	Day	# of Moulds	Type of Sleeper	Quantity	Amt. of concrete needed	Setup Flag
1	1	1	44	275	10	-1
2	2	1				0
3	3	1				0
4	4	1				0

Figure 5.2: The production information database

This database was integrated with the simulation model using ADO integration technology since ARENA software supported such technology. A special Read/Write module was enabled to link the type of integration with different external database files of different formats. This integration enabled the simulation model to read sequentially day-by-day orders with its relevant production information.

5.2.2 Development of Labour Information Database

The Access database was developed as a core database and user interface tool so that all labour information including crew formations and other detailed information regarding each worker was stored. The purpose of developing such a database was to provide the simulation model with the proposed allocation plan produced by the optimisation engine and to store the evaluated one. In addition, all optimisation initial inputs required during evolution phase and resulted outputs (suggested allocation plans) were stored in the database. This database was integrated with the searching engine using DAO technology as the Access database supported such integration technology. The required labour information in terms of crew formation was filtered using SQL queries. A collection of crews formed the required proposed allocation plan by the optimisation module. In addition, SQL was used to sort an ascending population of costs by which selection strategy would select the minimum costs for the population size. The Access database allowed the storing and retrieving of simulation input data, labour configurations in terms of allocation plans and simulation results.

5.2.3 Database Physical Model

The development of a database physical model for a labour allocation system was useful in identifying the structure of the relationship between the core engine (simulation+ optimisation modules) and its data supplier plant. A suitable interface was useful to create a communication vehicle with the allocation system components. This interface was used to control, display, and modify all labour inputs, optimisation outputs, and other related information. A well-designed user interface can satisfy the design support needs and encourage database use, Moore, G. (1989). Figure 5.3 shows the developed interface for the 'SIM_Crew' database.

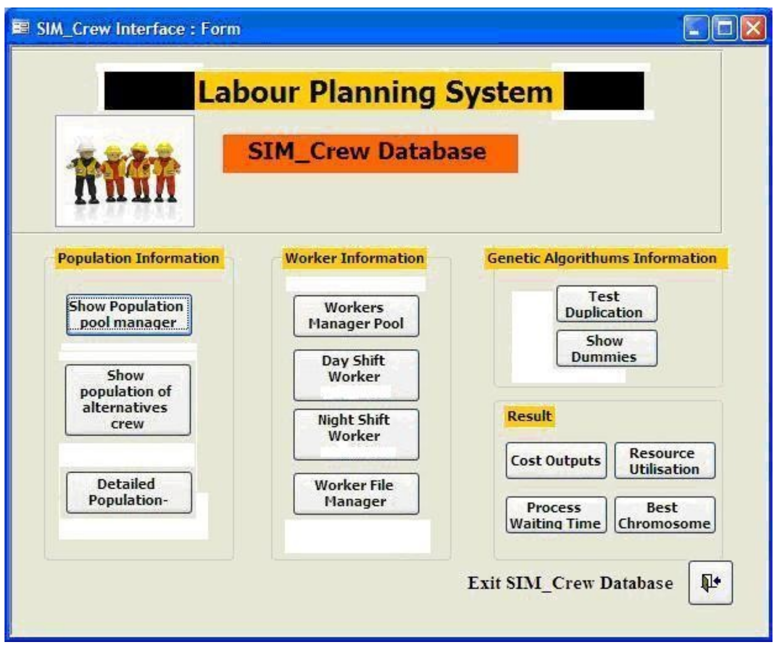


Figure 5.3: 'SIM_Crew' database interface

Figure 5.3, the developed interface shows four categories of information: population, worker, genetic algorithm, and results. The population category provides information about the population pool (pool of generated crew indices), alternative crews available for each process, and detailed population in terms of visualising formation of each crew of workers. The worker category provides information about each worker in terms of qualifications, working shift, production section, and hourly rate. The day and night shift workers can be displayed individually. The worker file manager is used to edit/add worker information.

The Genetic Algorithm category was used to show duplicated allocation plans, if found. In addition, a number of dummy resources were visualised in this category in response to simulation programming requirements (explained in chapter 7, section 3.2). In the last category; allocation cost, resource utilisation, process-waiting time, and the best allocation plan were displayed for better analysis. SQL played a vital role in retrieving the required labour information in the mentioned categories. The labour information inputs for this database were collected using the data collection methodology applied in chapter 4, section 2.

The next subsection describes the development of the physical database model depicting how the model was implemented physically and technically in the proposed allocation system.

5.2.4 Design of Data tables and relationships

In order to ensure quick locating or access to any specific crew member in any crew alternative formation and other related specifications of workers, a relational database was developed. The purpose of developing a relational database was to structure the storage of information in a way that future development, such as adding or removing a process, worker, or other related details to be facilitated in a flexible manner. In addition, the SQL facility, which Access database can provide, was useful to enable the search for a particular record. SQL was used in the optimisation phase to arrange stored cost information in a way that selection was achieved for a population size with minimum costs over all generations. The designed database is referred as ‘SIM_Crew Database’ and it was controlled using a developed interface shown in figure 5.4.

Relational databases model data objects were considered as two-dimensional tables. Each table was called an entity and represented a real world object of interest. Entities have relationships, logical associations with each other and consisted of a number of attributes.

Instances of entities, which differ in the values, contained for certain attributes and were represented as rows in the two-dimensional table. A primary key identified each instance uniquely; relationships were modelled by foreign key references of primary keys of the linked table. To modify database structure and manipulate data, the Structured Query Language (SQL), based on relational algebra, was developed. A relational database contains tables that are related. Related tables contain fields that match, ITS@ Pennsylvania State University (2008). For example, a Process table was related to a Crew table because they both contained a filter for Crew ID. The purpose of a relational database was that each piece of information only needs to be sorted once; otherwise, several updates would need to be made in several different places, which could be cumbersome and lead to inconsistencies if not carried out accurately.

The purpose of developing a relational database for 'SIM_Crew' system enables the designed system to be more flexible in terms of adapting any number of processes, any number of shifts, any number of crews, and any number of workers. By having lists (workers', crews', or processes' lists) that cross reference each other, a flexible scenario was built and created.

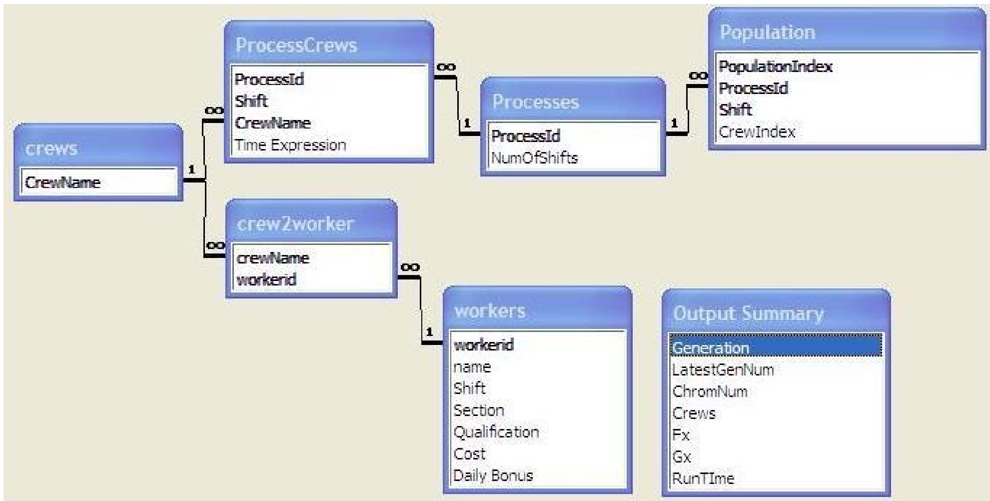


Figure 5.4: Relational database for 'SIM_Crew' system

As figure 5.4 shows having a list of workers, crews, processes with relational attributes allocated to them by defining additional lists, for example the *crew2worker* list defines which worker belongs to which crew by pairing them up.

Tables were created in Access database to be integrated with each other for further searching and information retrieval. See figure 5.5 for 'SIM_Crew' database data tables.

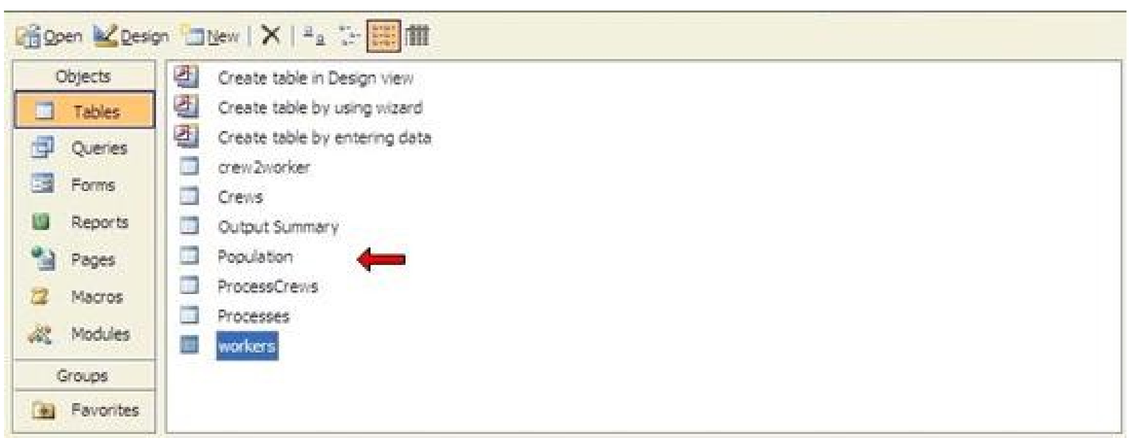
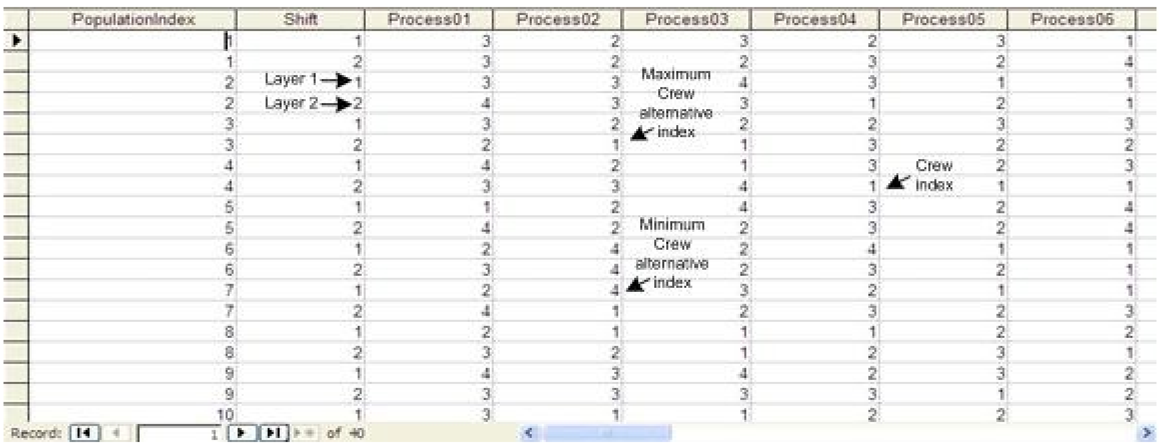


Figure 5.5: 'SIM_Crew' database data tables

In the table list shown in figure 5.5, each data table was considered as a database and a relational database model was developed to link up all of these tables. The description of each data table was necessary to gain an understanding of its' contents and its role whilst searching for the best allocation plan for operators.

The first data table is called a *population* and this table was used to provide an initial population of indices, these indices referred to a crew alternative number for each process in each shift. See figure 5.6 for the initial crew's indices, which were generated as an initial feasible solution.



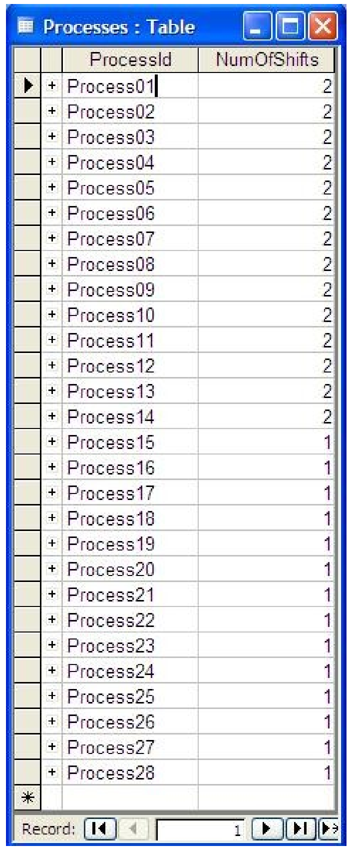
PopulationIndex	Shift	Process01	Process02	Process03	Process04	Process05	Process06
1	1	3	2	3	2	3	1
1	2	3	2	2	3	2	4
2	1	3	3	4	3	1	1
2	2	4	3	3	1	2	1
3	1	3	2	2	2	3	3
3	2	2	1	1	3	2	2
4	1	4	2	1	3	2	3
4	2	3	3	4	1	1	1
5	1	1	2	4	3	2	4
5	2	4	2	2	3	2	4
6	1	2	4	2	4	1	1
6	2	3	4	2	3	2	1
7	1	2	4	3	2	1	1
7	2	4	1	2	3	2	3
8	1	2	1	1	1	2	2
8	2	3	2	1	2	3	1
9	1	4	3	4	2	3	2
9	2	3	3	3	3	1	2
10	1	3	1	1	2	2	3

Figure 5.6: Initial population of indices provided by population data table

The crew index for each process for each working shift was generated using a Monte Carlo Sampling technique (the algorithm is explained in chapter 7, section 3.1). The supporting VBA language, embedded in ARENA software, was used to encode the Monte Carlo Subroutine. The upper boundary of a crew alternative for each process was defined using a special program routine to generate a less than or equal to crew index.

Monte Carlo Sampling was used to generate uniform random variates between index 1 as minimum crew index and the maximum crew index, which was already defined for each process, see chapter 7, section 3.1 for the crew index boundary restrictions formula.

To add more flexibility regarding number of processes, and number of shifts assigned for each process, a *processes* data table was developed to achieve such flexibility. This table was linked with the previous population table as each row of the generated population had process IDs (from 1 to 28 as presented in chapter 5) and the number of shifts (day/night shifts), see figure 5.7 for the pool of processes, for both shifts.


Processes : Table

ProcessId	NumOfShifts
Process01	2
Process02	2
Process03	2
Process04	2
Process05	2
Process06	2
Process07	2
Process08	2
Process09	2
Process10	2
Process11	2
Process12	2
Process13	2
Process14	2
Process15	1
Process16	1
Process17	1
Process18	1
Process19	1
Process20	1
Process21	1
Process22	1
Process23	1
Process24	1
Process25	1
Process26	1
Process27	1
Process28	1

Record: 1

Figure 5.7: Pool of processes provided by population data table

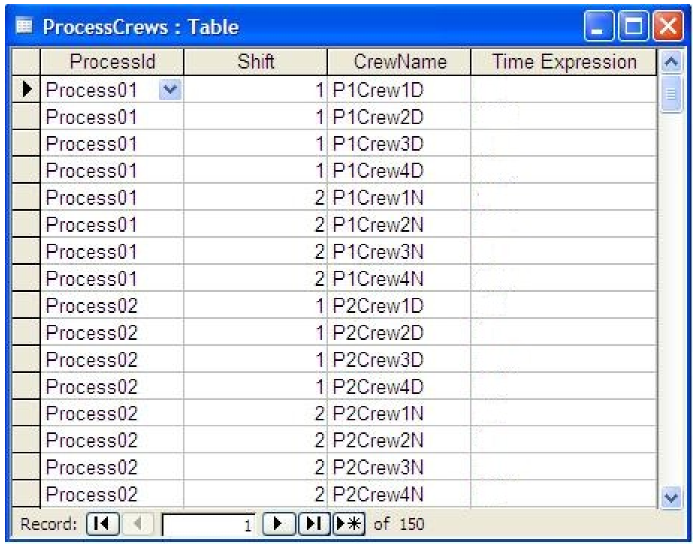
The *workers* data table was used to accommodate full details of each worker; these details involved worker ID, name, working shift, place of working, qualification, hourly wage, and daily bonus depending on skills. See figure 5.8 for the human resources information regarding production section 2 workers : Table

workerid	name	Shift	Section	Qualification	Cost	Daily Bonus
1	w01	Day	2	Operative		
2	w02	Day	2	Operative		
3	w03	Day	2	Operative		
4	w04	Day	2	Operative		
5	w05	Day	2	Charge Hand		
6	w06	Day	2	Charge Hand		
7	w07	Day	2	Operative		
8	w08	Day	2	Operative		
9	w09	Day	2	Operative		
10	w10	Day	2	Operative		
11	w11	Day	2	Operative		
12	w12	Day	2	Operative		
13	w13	Day	2	Operative		
14	Nw01	Night	2	Operative		
15	Nw02	Night	2	Charge Hand		
16	Nw03	Night	2	Operative		
17	Nw04	Night	2	Charge Hand		
18	Nw05	Night	2	Operative		
19	Nw06	Night	2	Operative		
20	Nw07	Night	2	Operative		
21	Nw08	Night	2	Operative		

Record: 1 of 63

Figure 5.8: Pool of workers provided by workers data table

This table was linked with a *crew2worker* table, in which each of the process workers, at any working shift, with any qualification, might be involved in any crew of workers depending on the qualifications and skills required. In addition, a *ProcessCrews* data table was developed to store crew alternatives available for each process for each working shift. Each crew of workers had a capability of finishing a job within a particular process time. This table was developed to provide a processes table with the required possible crew alternatives. See figure 5.9 for the *ProcessCrews* table



ProcessCrews : Table

ProcessId	Shift	CrewName	Time Expression
Process01	1	P1Crew1D	
Process01	1	P1Crew2D	
Process01	1	P1Crew3D	
Process01	1	P1Crew4D	
Process01	2	P1Crew1N	
Process01	2	P1Crew2N	
Process01	2	P1Crew3N	
Process01	2	P1Crew4N	
Process02	1	P2Crew1D	
Process02	1	P2Crew2D	
Process02	1	P2Crew3D	
Process02	1	P2Crew4D	
Process02	2	P2Crew1N	
Process02	2	P2Crew2N	
Process02	2	P2Crew3N	
Process02	2	P2Crew4N	

Record: 1 of 150

Figure 5.9: Pool of crews provided by ProcessCrews data table

In addition, a *ProcessCrews* table was linked with the *Crew* table to retrieve the possible crew alternative names. A *Crews* data table was then used to present each possible collection of workers in terms of including the involved workers ID. This table was designed to outline the contents of each crew. See figure 5.10 for the pool of crew formations available for each process.

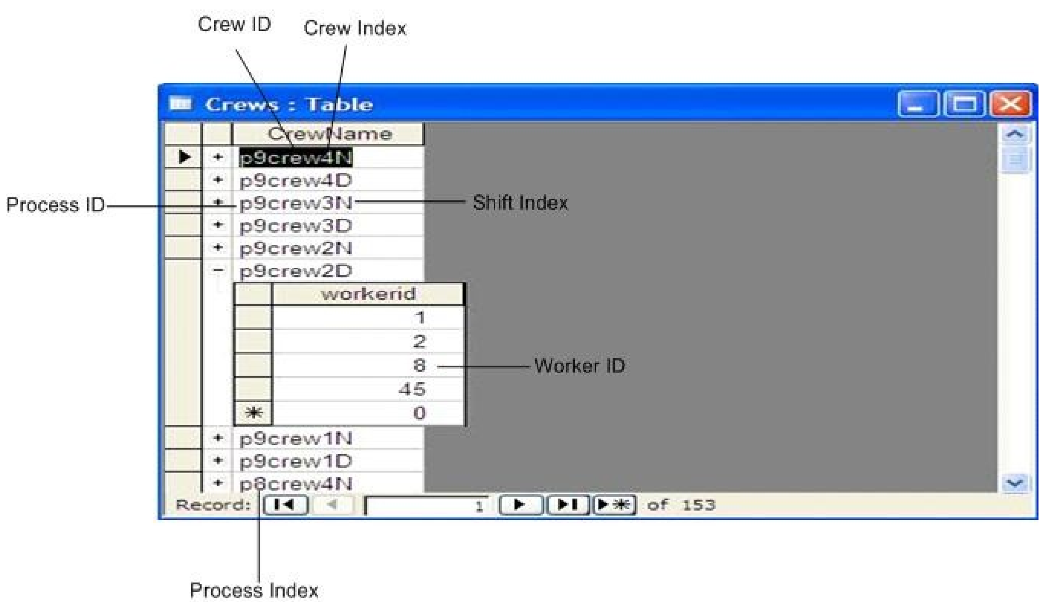


Figure 5.10: Pool of crews provided by ProcessCrews data table

In this table, each crew formation available for a process was presented in terms of a worker indices collection. A number of crew alternatives available for a process was also presented. *crew2work*er was the same as *Crews* table, the only difference being that each crew was presented with the index of the worker, rather than a crew formation. The crew alternative list was obtained from the production manager based on his/her experience in the job-shop environment.

5.2.5 Design of Queries

Queries were used to inquire, filter or combine information from different data tables, for grouping the information to yield new tabular objects. Figure 5.11 shows a list of queries used in 'SIM_Crew' database.

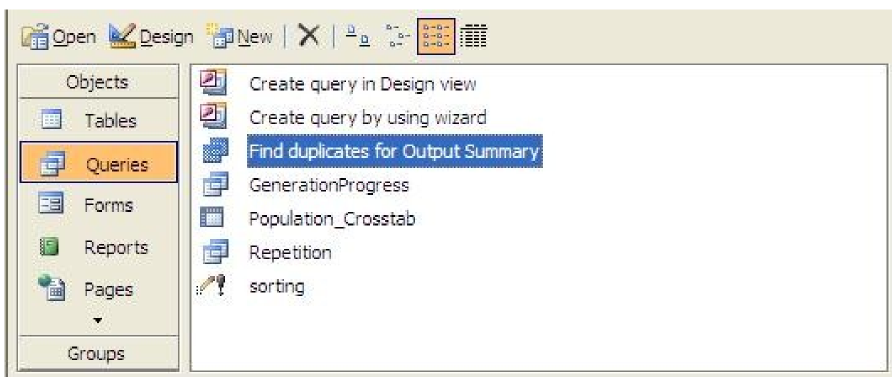


Figure 5.11: List of queries used in 'SIM_Crew' database

In *Find duplicates for Output Summary* query, double checking was required to investigate any duplication that may have taken place at any generation. This duplication involved checking the formation of crews only; duplicating of throughput times or costs being permitted. The duplication structure for developing *Find duplicates for Output Summary* query is shown in figure 5.12

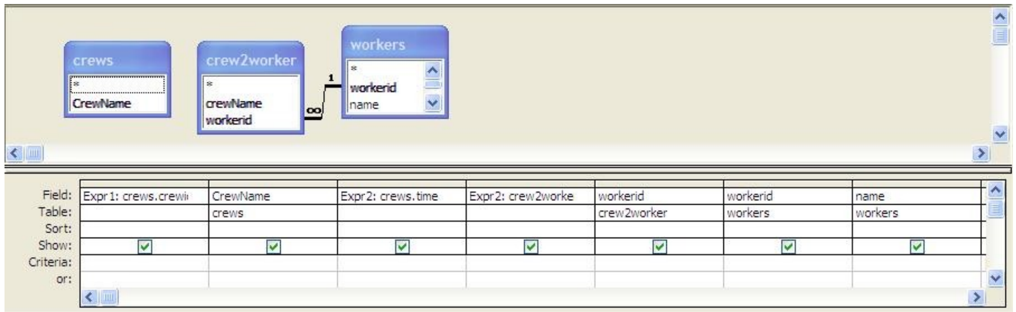


Figure 5.12: List of queries and design example

In most of the development, SQL statements were used rather than query tables, and were explicitly defined in Access. This was essential to enable the retrieval of database information from external applications as well as for VBA coding. An example of SQL statements for the above query (figure 5.12) is given below:

SELECT crews.crewid AS Expr1, crews.CrewName, crews.time AS Expr2, crew2worker.crewid AS Expr2, crew2worker.workerid, workers.workerid, workers.name
FROM crews, workers INNER JOIN crew2worker ON workers.workerid = crew2worker.workerid WHERE ((([crew2worker].[crewid])=[enter crew number]));

5.3 CHAPTER SUMMARY

In this chapter, a labour information database was developed in order to provide the core of the crew allocation system (both simulation and optimisation modules) with the required information. In addition, this methodology was useful in terms of retrieving the required labour information from the database to be fed, to the allocation core and in storing its outputs. The labour information exchange process to generate more possible allocation plans was enabled by using such a database.

The modelling process of the 'SIM_Crew' databases was presented. The structure of the developed databases was illustrated and integration mechanisms of those databases with the core of the allocation system were addressed. Two types of databases were suggested as a convenient accommodation of both production and human resource information.

The development process of the relational database model was described in detail and all of the relevant tables of the designed relational database were explained. All labour information using data collection methodology (explained in chapter 5, section 2.2) were store in the developed database to be used as labour information supporter.

CHAPTER 6

DEVELOPING A SIMULATION PROTOTYPE FOR THE SLEEPER PRECAST MANUFACTURING SYSTEM

6.1 INTRODUCTION

In this chapter, the development of a simulation model for a sleeper precast manufacturing system is discussed in detail. ARENA Rockwell Automation simulation software was selected to be used as the appropriate software. The simulation model was developed based on a number of assumptions. The developed simulation model consisted of two sub-models developed individually to enable an easier and flexible modelling process.

The first sub-model simulated the logic of the batch plant system and the second one simulated the logic of the production processes. By combining these two sub-models together, the whole simulation model was obtained. However, different combinations of crews of workers in terms of possible allocation plans were also evaluated throughout the developed model in order to identify the best allocation plan.

A simulation software limitation is addressed while simulating a process with multi-working shifts. This limitation was overcome by developing a special template PROCESS module. A verification and validation process was conducted to guarantee validity of the developed model. A simulation run is illustrated in order to generate preliminary results being useful in assessing and analysing the outputs of the current adopted 'As-Is' allocation plan. 2D and 3D visualisations are developed to enable the process of verifying and validating the model.

6.2 SIMULATION SOFTWARE REVIEW AND SELECTION

Two general purpose simulation software tools, “ARENA” (Rockwell Automation) and “AnyLogic” (XJ Technologies) were evaluated in depth. The criteria used in the evaluation process were: ease of building a simulation model, possibility of integration with Microsoft languages, setting of resources to a process, ease of building prototype and integration of the database, connectivity with standard programs and purchasing cost.

In AnyLogic software, database connectivity in terms of professional components (Query, Key Value Table, Insert, Update, Text file) and professional model debugging (e.g. Breakpoints, Watching all Model Variables including Expressions Evaluation, Line-by-Line Execution, etc) were only available on the professional edition of AnyLogic, (XJ Technologies, 2005). The assigning of resources to a process module was not easy as it needed to place all resources in a pool before any resource allocation can take place.

The resource pool concept in the software makes resource assigning to a process more difficult to the programmer especially when dealing with more than one resource assignment trail. In addition, the high purchasing price of the professional AnyLogic programme provided the motivation to search for software alternatives.

ARENA is the SIMAN simulation language, which provides both a powerful foundation for modelling complex systems and a fast simulation engine for efficient analysis of design alternatives (Bapat and Sturrock 2003). ARENA is based on modules and modelling structures which are flowchart data objects. The ARENA interface is a separate window in which users can edit, design and debug it with Visual Basic Code and forms. Users can define procedures and functions in blocks with Visual Basic for Applications (VBA) ARENA by Kelton, et. al (2008). The Arena product suite is designed for use throughout an enterprise, from strategic business decisions, such as locating capacity in a supply-chain planning initiatives, down to operational planning improvements, such as establishing production line operating rates, Bapat and Sturrock (2003). Discrete event simulation modelling is adopted in this research because it provides a flexible tool for modelling detailed processes and it is the most commonly used methodology in production process modelling, Banks, et. al (2003). VBA is used as a supporting language to enrich the capability of the developed simulation model for better searching capabilities.

The specific modelling requirements for the 'SIM_Crew' allocation system fits with the capabilities of Rockwell Software's ARENA modelling language. The Arena graphic simulation system was designed for building computer models that accurately represent an existing or proposed application, such as schedule optimisation, increased throughput, cost reduction, and resource utilisation. The power of animation which ARENA provides in terms of 2D and 3D is useful for presentation and validation purposes. ARENA integrates all simulation, related functions, animation, input data analysis, model verification, and output analysis into a single simulation modelling environment.

Microsoft office database, Excel and Access can be integrated easily with ARENA software using Microsoft integration technologies. In addition, each process module has its own resource pool which makes the resource allocation process easier.

6.3 ASSUMPTIONS USED IN THE DEVELOPMENT OF THE SIMULATION MODEL

A number of assumptions have been made in order to simplify the modelling process of the sleeper precast manufacturing system being investigated. They are:

- Two production sections are considered in developing the simulation model.
- Two working shifts are considered while developing the current prototype.

- An average process time of each crew of workers is considered as a function of crew efficiency.

- Crew formations (skill matrix for each alternative) have been provided by the production planner. The historical records and production planner's past experience have been used to form each skill matrix.

- A process cannot be started without availability of all crew members.

- First-Come First-Served (FCFS) is adopted as a processing priority rule.

- High level modelling is applied to simulate the processes in the manufacturing system.

- Each order is processed by the same processing machines.

- Any shared manufacturing machine can process only one mould at a time.

- Each crew member is involved intensively to carry out the production process being carried out. The members work continuously to finalise the process being carried out.

- Each worker within a crew of workers is responsible for completion of his/her job.

- Any breakdown in any of shared resources or labour supply is not considered in this model.

- The whole responsibility of carrying out a job within a process, is handed to the next shift crew of workers, when the remaining time of the current working shift is insufficient to finish a process.

- The crew must remain together to complete all tasks even if some crew members are not fully utilised to complete the process before moving on to the next process.

6.4 COMPONENTS OF A DISCRETE EVENT PRECAST LABOUR INTENSIVE SIMULATION MODEL

Discrete event models are made up of entities, attributes, and events. An entity represents some object in the real system that must be explicitly defined, Dale and Lewis (2004). The entities considered while developing this simulation model were:

- Orders, which enter the manufacturing system when a concrete mould is ready to be seized.
- Concrete batches, the capacity of the concrete holding hopper when the mix is ready to flow into it.

Resources used in developing this simulation model were:

- Machines including casting, de-moulding, and other shared physical resources.
- Workers can be considered as substantial resources in this study.
- Forklifts are used to move produced items from the production area to the open stockyard area.

6.5 DEVELOPMENT OF SLEEPER PRECAST LABOUR-INTENSIVE SIMULATION MODEL

The simulation model was developed to imitate the manufacturing system of the sleeper precast concrete sleepers. The developed simulation model was used to analyse and examine the current applied crew allocation plan to determine the possibility of achieving a better allocation plan in terms of reducing allocation cost, optimising labour optimisation and minimising process-waiting time. The simulation model was developed as a platform to evaluate possible allocation plans.

For modelling simplification purposes, the sleeper precast manufacturing system being investigated was divided into two zones: *batch plant zone* and *production processes zone*.

A sub-model of each zone was then developed to imitate all processes carried out in each zone. After developing sub-models, integration was facilitated to form the required simulation model. The developed simulation model was decomposed into two sub-models. These sub-models led the modelling processes simpler to use and increased flexibility.

- Batch plant (Mixer process)
- Production processes

6.5.1 Sub-Model 1: Modelling of the Mixer Process

The simulation model was developed to imitate the process of preparing and providing concrete to the production system. The logic of developing a simulation model for mixer operation in a precast production system was discussed earlier in chapter 3, section 5.3. See figure 6.1 for the simulated batch plant operation.

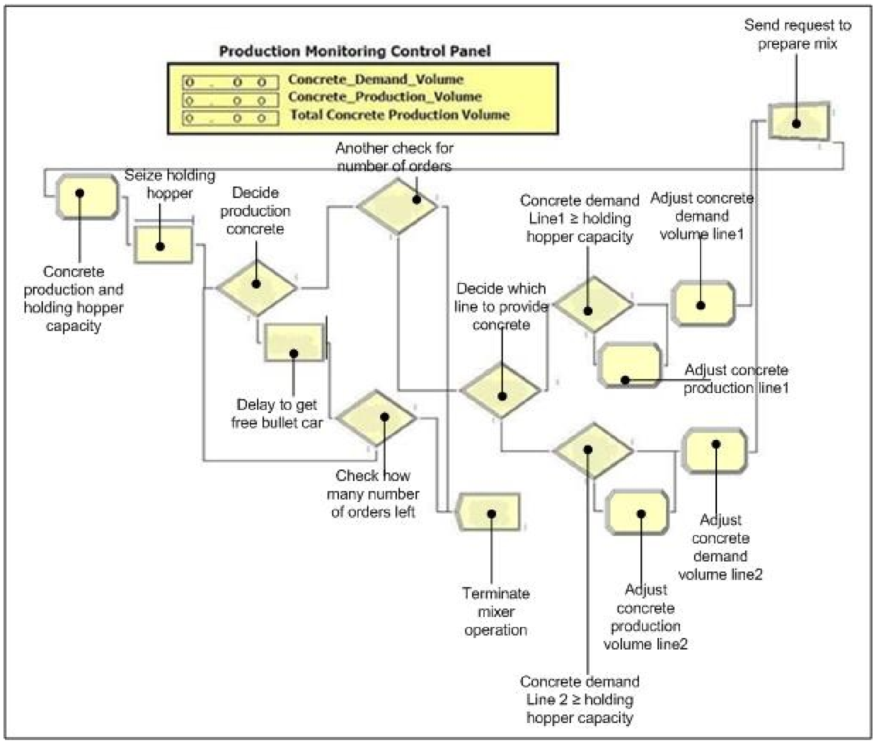


Figure 6.1: Simulation of the batch plant area

In the logic above, the holding hopper is seized to provide concrete when needed. The required variables were defined to represent the amount of the concrete needed for the casting process and the current amount of concrete production. The mixer continues producing concrete as long as concrete was required to be moved to the casting process zone and in particular the casting machine hopper. The mixer was shut down when the planned number of moulds were filled with the required amount of concrete. The concrete production monitoring control panel was designed to follow the fulfilment of the casting machine hopper's requirement with full consideration of the remaining concrete required and the current production run. The amount of concrete required to fill the batch of moulds and how many times the holding hopper needs to be filled to provide the batch requirements of concrete decides on the numbers of mixes to be produced. Simulation sensitivity analysis was used to generate some useful decision-making tools for concrete batch plant, Zayed and Halpin (2000).

6.5.2 Sub-Model 2: Modelling of the Production Processes

All logical relationships needed to simulate the production zone are shown by the developed flowchart in chapter 3, section 5.3. In figure 6.2, each production section is simulated with a basic animation for each of them. Two production sections with a shared mixer to provide concrete for each when needed were simulated.

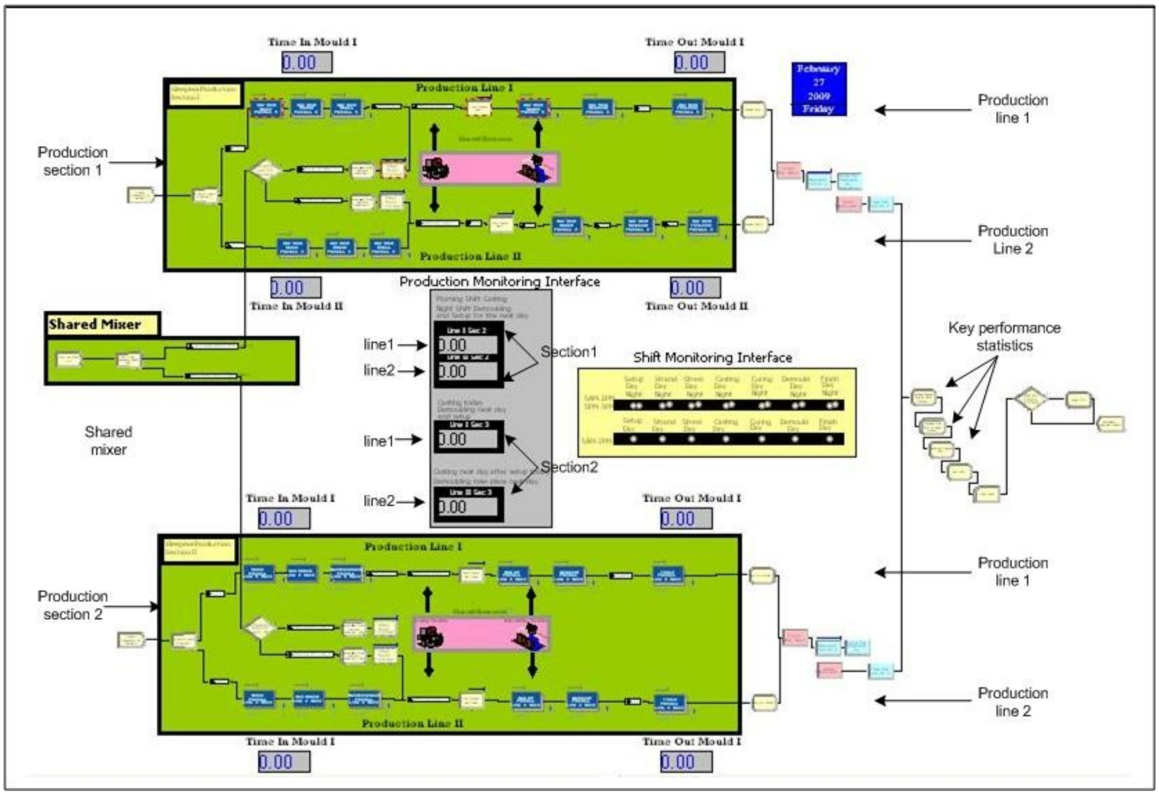


Figure 6.2: Snapshots of simulation model for the manufacturing system

Each production section was simulated according to the developed process map presented in *appendices H and I*. The simulation process was achieved by placing required resources and defining the process time for each module. See figure 6.3

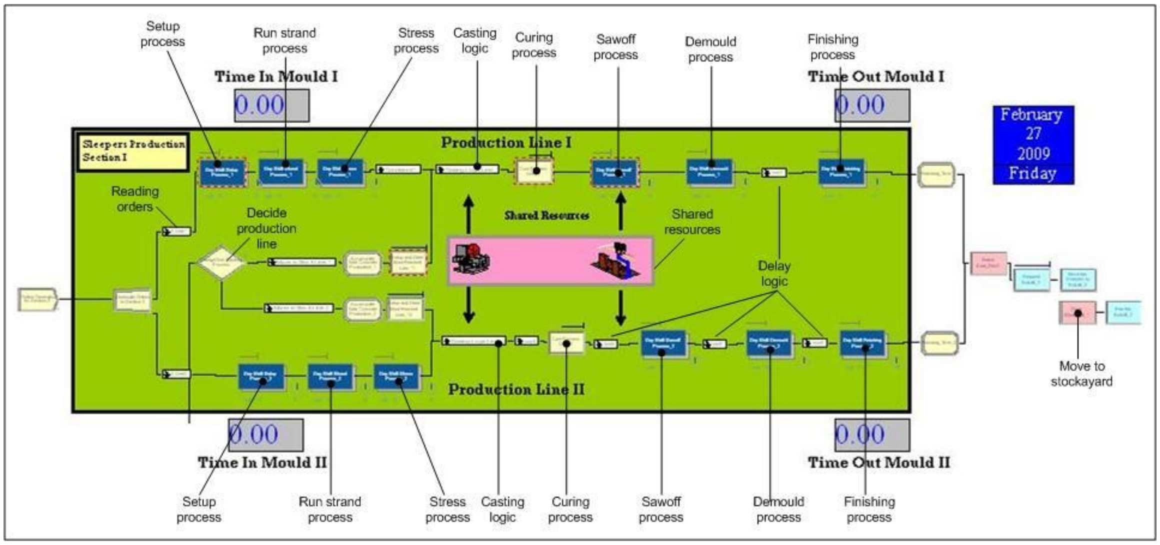


Figure 6.3: Snapshot of the simulation model for a specific production section

In figure 6.3, the logic required to distribute concrete between each production line was developed according to a signal sent from the casting zone where a batch of concrete was called for. A number of delay modules were used as part of the modelling requirement.

6.6 LIMITATION OF THE ADOPTED SIMULATION SOFTWARE

The success of simulation modelling depends on the correct selection of the simulation software itself for the purpose of modelling. A system has been developed for the purpose of providing support for users when selecting simulation software, Hlupic and Mann (1995).

Several surveys revealed that simulation software were predominantly easy to use, with good visual facilities, but too limited for complex and non-standard problems, too expensive and incapable of providing adequate guidance in experimentation, Hlupic (1999). One of the most important features required in many labour-intensive firms is shift working which is necessary to augment productive capacity and to ensure efficient use of expensive equipment. Shift working can vary considerably in its specific characteristics. Continuous shift systems require weekend working whereas discontinuous systems occur in organisations that operate Monday through Friday. The shift working scenario varies with respect to start and stop times of workers, length of the shift, and length of time off between shifts.

Despite the major benefits associated with simulation software, simulation is not a perfect technology since difficulties and limitations arise in the simulation of manufacturing where multi-shift systems are in operation. However, it is useful to make a distinction between limitations created by the analyst, and limitations which are inherent in the technique itself, Dov (1969).

Two limitations were found while developing the current simulation model described in the section below. In addition, Human performance must be modelled in order to impact system design, performance, and cost, Allender (2000).

6.6.1 The Normal PROCESS Module: Difficulties and Limitations

The researchers faced two major limitations while simulating the multi-shift precast concrete labour-intensive manufacturing system. These limitations resulted in infinite loops and overflow utilisation rates when using the normal PROCESS module to simulate multi-shift labour-driven parallel processes. Problems associated with a small resource scale could have been solved with the current simulation facilities but larger resource scales of a dynamic nature. The application of different resources for each cycle efficiently could not be solved using capabilities of the ARENA software. Details of these limitations are discussed below:

- **First Limitation:** There is a limitation in the ARENA software in terms of adopting two working shifts for different resources to carry out the same job. A number of trials were conducted to model the process with two different resources involved, each of them subject to a particular working time shift. The trials were as follows:

  1. Place all the resources into the process pool, and then set each of them to follow a particular shift pattern using the calendar. ARENA was found not to allow this type of modelling and the process went into an infinite loop.

  2. Split the process into two process pools, the first one contains the day shift resources and the second one contains night shift resources. A decision model was used to decide which shift is operating according to a condition that if the capacity of the resource is numerically equal to one then the resource is on active working shift.

  3. VBA codes were written to set the capacity of non active shift resources to zero. Resource capacities are set to one when the working shift is active.

  4. An issue was identified when the remaining shift time is not enough to progress the current process. Two scenarios were developed to overcome this problem: progress with the remaining time and handover the remaining of the job to the next shift crew. However, this type of modelling was not feasible within ARENA simulation since PROCESS block consumes the whole process time before releasing the entity.

  5. A resources set concept was applied to model the shift problem; resources were placed into the set. A selection rule was chosen to represent the "Largest Remaining Capacity" but unfortunately it was found that only one resource could be selected at a time, ignoring all others. This eventually affected the utilisation of other used resources.

- **Second Limitation:** A set of processes being assigned by the SEIZE module created a conflict while dealing with calendars or schedules. This limitation caused overflow utilisation where some of the resource utilisation exceeded 100%. The developed system involved four parallel concrete moulds, each mould being processed through eight production processes, and each production process has several resources required to carry it out. The "Preempt" scheduling rule did not handle this type of resource seizing, see figure 6.4. The following interpretation was concluded and discussed with the ARENA software consultant.

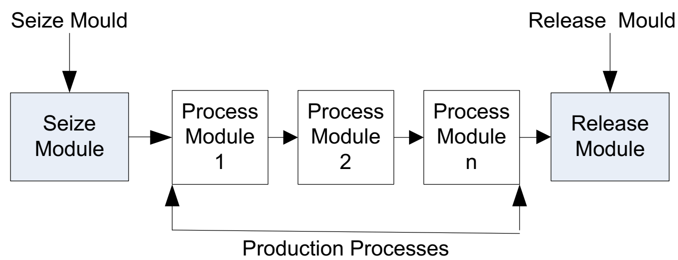


Figure 6.4: The main cause of shift limitation

It was noticed that if the entity that originally seized a resource was still ongoing, then the resource could not be preempted (See file titled PREEMPT BLOCK, rank 5). This limitation caused the overflow of the scheduled utilisation to be greater than 100% when designing one or more than one working shifts. It was concluded that Preempt was the cause of the limitation as it was not designed to deal with more than one "*SEIZE"* module each of them having an assigned resource.

The normal PROCESS module is discussed in details as in the following section:

6.6.2 The Normal PROCESS Module

The normal PROCESS module consists of one pool of resources; this pool should contain at least one or more resources. Different levels of priorities to a given process can be defined. Delay time can be defined as a deterministic or probabilistic value;

statistical distributions can be defined to add the required randomness to the delay time. See figure 6.5 for the PROCESS module.

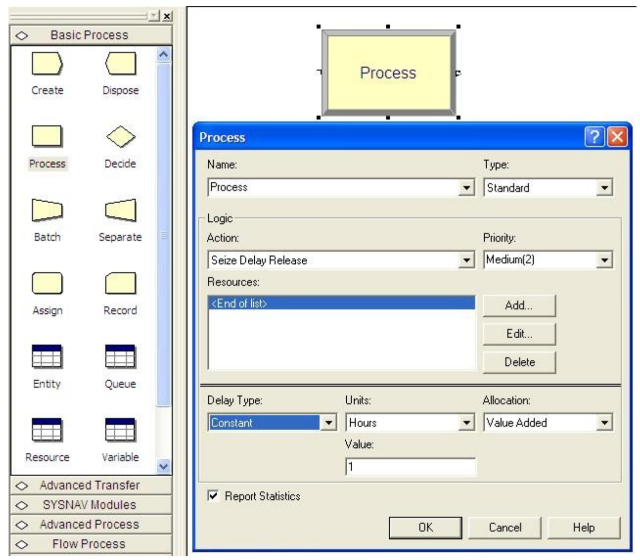


Figure 6.5: Snapshot of the normal process module

Placing resources into the resource pool is necessary to enable execution of the PROCESS module. The quantity of each assigned resource should be defined in order to enable the process to identify its resources. See figure 6.6 for the resource quantity.

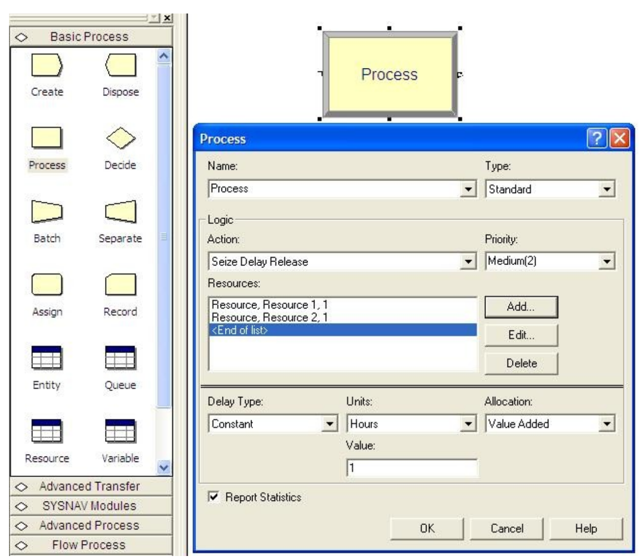


Figure 6.6: Snapshot of the normal process module

A working shift can be defined using the Calendar Schedules option, time pattern enables a definition of each shift during a specific period of time. Figure 6.7 shows the calendar facility provided by ARENA simulation software.

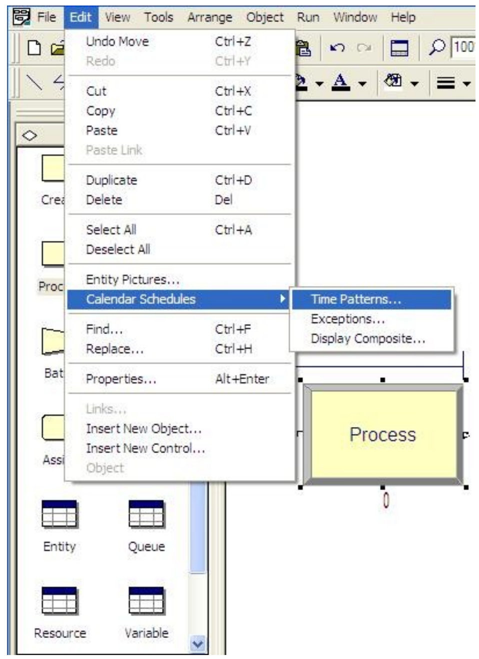


Figure 6.7: Snapshot of the normal process module

Daytime shift can be identified by alternating resource capacity, when a resource is available then its capacity is set to equal 1 and if the same resource is not available then its capacity is set to zero. Saturday and Sunday could be excluded from working days.
In order to overcome this limitation, a special PROCESS module was developed for multi-shift resource modelling:

6.6.3 The Developed Special Template PROCESS Module

To overcome this limitation, a special process model was designed to include more than one resource pool; each resource pool having its own shift system. The day shift workers were placed into the first workers pool and the night shift workers were allocated into the second workers pool. Figure 6.8 shows a multiple pool of resource for a process.

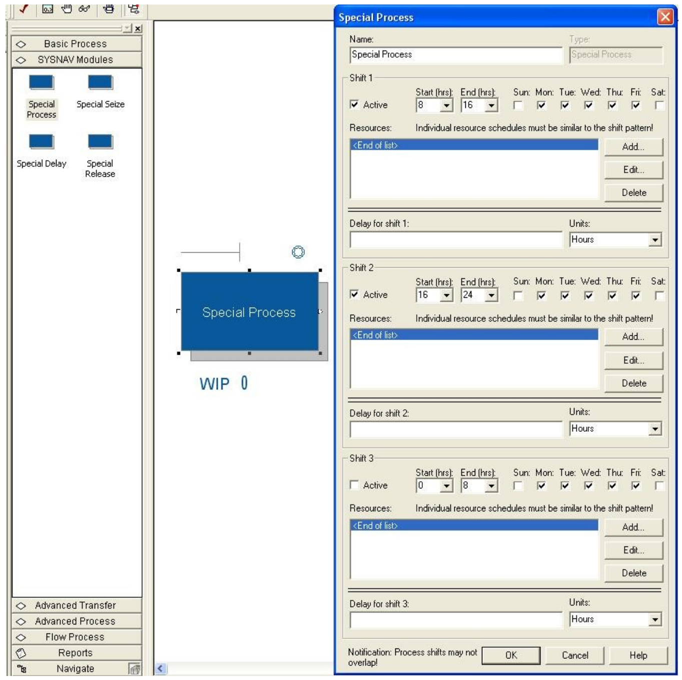


Figure 6.8: Snapshot of the proposed PRCOESS module

The process template was designed to include three pools of resources; days and working hours of each pool were controlled through defining a working shift. The control panel for each pool consisted of an *Active* tick box which was used to activate the shift pattern. Working hours were then defined through a drop menu designed for that purpose. *Tick* boxes control being the choice of any day during the week to be a valid working day. A pool of resources is available to place both resource name and resource quantity into it.

Delay time was designed to be a deterministic duration as process time nature was deterministic in this problem.

As it can be seen in figure 6.8, for each resource pool an "Add" button can be used to add more resources to the pool and Edit can be used to change name or quantity of the resource. The instantaneous utilisation was calculated using the current shift settings. To calculate the scheduled utilisation, each set of resources was scheduled according to its shift pattern. Different schedules were set for each resource pool. Figure 6.9 shows the schedule for a day shift schedule.

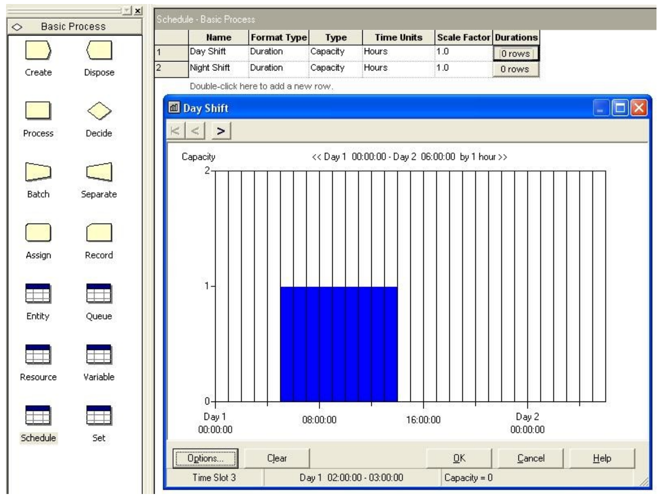


Figure 6.9: Snapshot of the day shift schedule

A night schedule can be defined by setting schedule capacity to 1: this means that during a particular period the available capacity is equal to 1 which reflects that the required resource is ready. A night shift schedule can be seen in figure 6.10

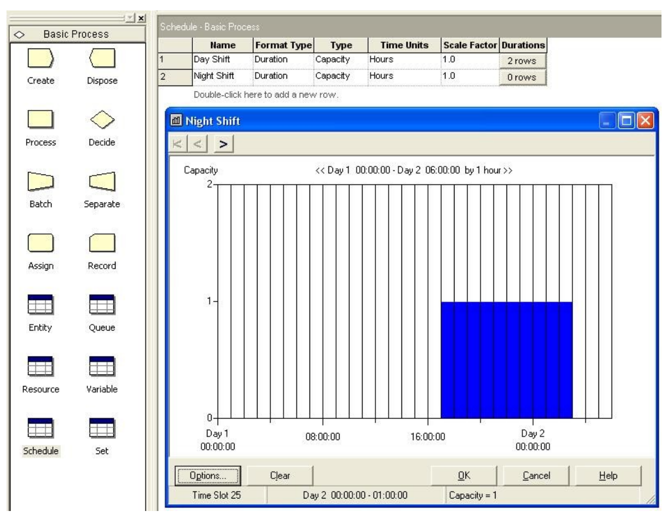


Figure 6.10: Snapshot of the night shift schedule

Each resource was assigned with its shift pattern (the schedule), this ensured no clashes between resources allocated to different shifts as there was more than one resource pool. See figure 6.11 for the schedule of two resources

Resource - Basic Process

	Name	Type	Schedule Name	Schedule Rule	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Failures	Report Statistics
1	Resource 1	Based on Schedule	Day Shift	Wait	0.0	0.0	0.0		0 rows	☑
2	Resource 2	Based on Schedule	Night Shift	Wait	0.0	0.0	0.0		0 rows	☑

Double-click here to add a new row.

Figure 6.11: Snapshot of the schedule of two resources

The objective of developing this template was to overcome the limitation of ARENA in terms of running more than one shift with different resources. The difficulty concerning handover of jobs when the time left for completion was insufficient and was solved using the developed template PROCESS since jobs could be handed over to the next shift crew when insufficient time was left. The one-pool limitation created a shortage in terms of providing real resources utilisation and a high completion time plus an extended run time for the model.

6.7 VERIFICATION AND VALIDATION OF THE SIMULATION MODEL

A number of verification and validation techniques can be used to verify and validate simulation models, Sargent (2005). In this study, three verification techniques were adopted to check the validity of the developed simulation model, as follows:

6.7.1 Verification of the Developed Simulation Model

Of the three techniques used to verify the logic of the developed simulation model, the process map was considered as an essential tool to provide a good feedback for rectification of the developed logic. Other visualisation techniques were used to check visually whether the current animation was similar to the actual one. The details of each verification technique are given as follows:

- **Process Maps**

Before constructing the simulation model, all process maps involving the overall logic of the manufacturing system and other relevant flowcharts were reviewed by the production manager. Each process map concerning a particular process was discussed with a senior chargehand of each process. The logic stated in process maps was therefore verified after structural interviews with the production manager and other chargehands.

- **2D Animation**

Initial verification was carried out by the researcher by observing the animation of the simulation entities to ensure that entities were travelling to the right location in accordance with the entity flow diagram provided by the process maps. In addition, simulation runs were presented to the production manager, supervisors and a wider group of operators during a number of structured interviews, to verify the developed model and determine whether the results were correct or not. The developed simulation model was verified by checking the sequence of the simulated processes. The process flow was tracked to see whether the product being produced was moving exactly as in an actual production process.

- **3D Proof Animation**

Proof animation was used to verify the developed simulation model. Proof Animation is a general-purpose post-processing animator designed for use with a wide variety of simulation tools, Henriksen (1997). (Post-processing means that it runs only after the simulation model has terminated). After running a simulation model, both a trace file and a layout file are generated and should exist for running an animation using Proof Animation. The post-processing approach offers advantages such as the ability to jump the time during the animation playback, to show all or a specific portion of the animation, and to accelerate or decelerate the viewing speed. The proof animation in the form of a 3D model was shown to the production manager and other senior planners to determine whether the simulated model was reflecting reality or not. The flow of processes and other processing details were presented to the production manager as a proof of verification.

6.7.2 Validation of the Developed Simulation Model

After running the “As-Is” scenario by the developed simulation model, it is important to determine if the simulation outputs are similar to the reality. The validation procedure used here was to estimate the production time for each production line and both production sections together to check the convergence of results with the “As-Is” outputs. After running a simulation model on a 24 hours basis, the results were compared with reality as follows:

1. Section 1 was isolated and processes were conducted on line 1. Then the simulated value was 19.2503 hours due to the approximation of the forklift speed. The actual value was 19.25 hours to process the whole line.
2. Section 1 was isolated and processes were conducted on line 2. Then the simulated value was 20.7503 hours due to the approximation of the forklift speed. The actual value was 20.75 hours to process the whole line.
3. Section 2 Line 1 was verified for one mould and the total time of processing a mould was equal exactly with the total hours needed to finish that mould in reality (24.75 hours).
4. Section 2 Line 2 was been treated as an isolated unit, that is, all restrictions imposed by line 1 were removed and a normal operation process was conducted on that line to check the total processing time needed to carry on all processes on it. The total production time for a mould was 24.76 hours while the simulation predicted the same time.

After adopting the developed PROCESS module (scheduled resources) in the model building process, the resulting model was validated using:

1. The simulation time of production section 1, line 1, was similar to the actual production time (2 sleeper gangs were produced within a period of two working shifts). 9.5 hours for the daytime shift was the simulation time to produce one sleeper gang and to cast the other production line. Ten hours and half for the night-time shift was enough to produce two sleeper gangs.

2. The simulation time of production section 1, line 1, was similar to the actual production time (1 sleeper gang was produced within a period of one working shift). 9.5 hours was the simulation time to produce one sleeper gang and to cast the other production line.

3. The simulation time of both production lines in production section 1, was similar to the actual throughput time.

4. The simulation model was run for one day operation and the resulting throughput was exactly equal to the current day production capacity of the manufacturing system.

5. The simulation run for five operation days resulted in production throughputs which were equal to the weekly production capacity.

In order to conduct the productivity validation, a production monitoring interface was developed to monitor the production achieved at each line. See figure 6.12 for the production monitoring interface

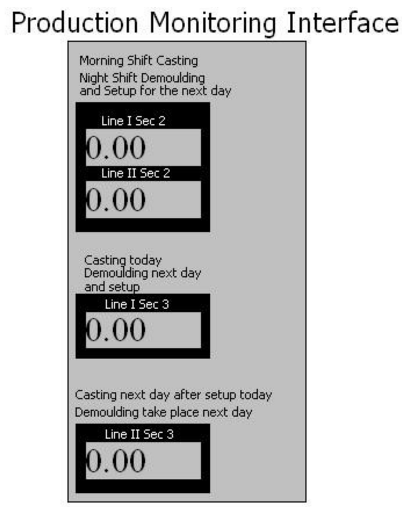


Figure 6.12: Snapshot of the shift monitoring interface

In this interface, production quantities produced in each production line for both sections were visualised in order to identify the simulated production rate. In addition, the proposed PROCESS module was validated in terms of scheduling functionality through developing a shift interface monitoring form. See figure 6.13

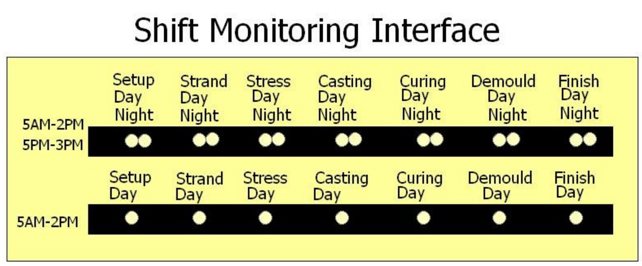


Figure 6.13: Snapshot of the shift monitoring interface for line 1, both production sections

In this interface, the progress of each process can be seen for both shifts. Each production line at section 1, was given a two shift monitoring bar with just one shift monitoring bar for each production line, at section 2.

The 'System Navigator' Company, the developer of the advanced PROCESS module for Rockwell, tested and validated the developed module through using it in a number of simulation models. All models were verified and validated with the partners as significant proof of the module reliability. In addition, the developed module was recommended by 'System Navigator' to the main producer company *Rockwell Automation* to consider it as advanced process module in the next version of the ARENA 13.0 software. This innovation will assist future researchers in their quest to resolve shift working issues in labour intensive simulation models.

6.8 RUNNING OF THE DEVELOPED SIMULATION MODEL: "AS-IS" SCENARIO

Before running the simulation model, all inputs required for running of the model were presented. The inputs required for running of the developed simulation model were then classified into the following categories:

- Production information: number of moulds, types of product, quantity of product. to be produced, amount of concrete needed to cast a mould, other setup flags.
- Process information: process name, action, priority, resources needed to carry out the process, process time.

Based on the production plan provided by the precast labour-intensive company, a simulation model was run to progress the required orders. Simulation is used to estimate some of the common performance measures, Law and McComas (1998).

A number of performance criteria were identified to measure performance of the manufacturing system. The results from the simulation were identified as: total cost of assigning labour and costs of using some substantial resources and utilisation of skilled operators. Some preliminary results are presented in the following section.

6.8.1 Preliminary Results

In this section, some preliminary results generated for current sleeper precast manufacturing system are presented. For the preliminary analysis, the effect of allocating different crews of workers to production processes was identified. Worker-oriented simulation allows the estimation of the workers' influence on the logistic system and the system's influence on the workers with a higher accuracy, Freudenberg and Herper (1998). Performance criteria were used to show the effect of the current labour efficiency on allocation cost and system performance.

After running the simulation model, the number of sleepers produced in section 1 and 2 were 12 and 6 sleeper moulds respectively. These production rates were the same as the actual production rate (within 6 days and 19 hours, section 1 can produce (2×6) sleeper moulds, and section 2 can produce (1×6)). The actual production plan was presented in chapter 4, section 5.

The "As-Is" crew allocation plan has returned a total allocation cost of £51199. This cost includes labour costs besides other physical resources costs. It showed a high utilisation of a number of multi-skilled chargehands in the night shift. See figure 6.14 for individual utilisation of each skilled worker

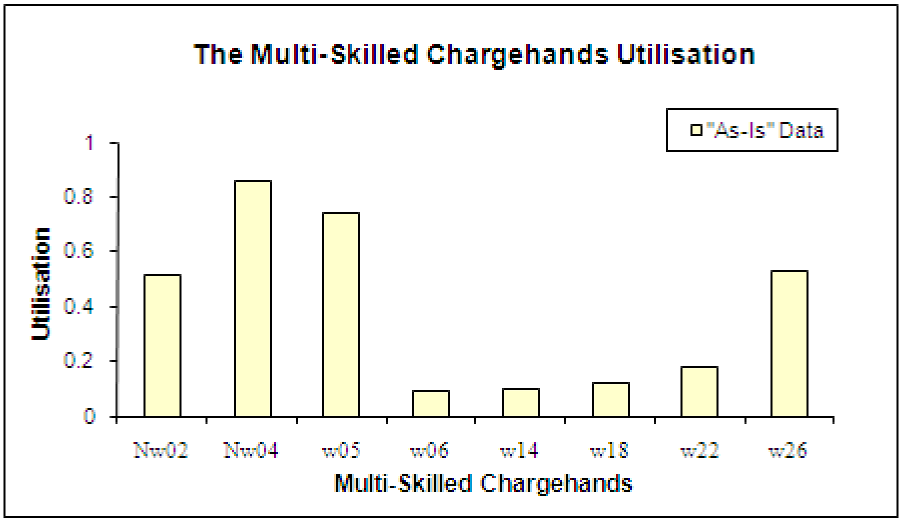


Figure 6.14: The multi-skilled chargehand utilisations

In figure 6.14, a high utilisation of multi-skilled chargehands was yielded since a number of them were involved in carrying out jobs along most of the production processes.

For multi-skilled operators, a number of them are involved along the flow of the production processes. Other less-utilised operators are involved to do a limited role in some processes due to insufficient skills. Those operators are often involved in other production sections to produce other precast products. Figure 6.15 shows that only 14 operators out of 30 for both shifts were heavily involved in carrying out jobs within the manufacturing system.

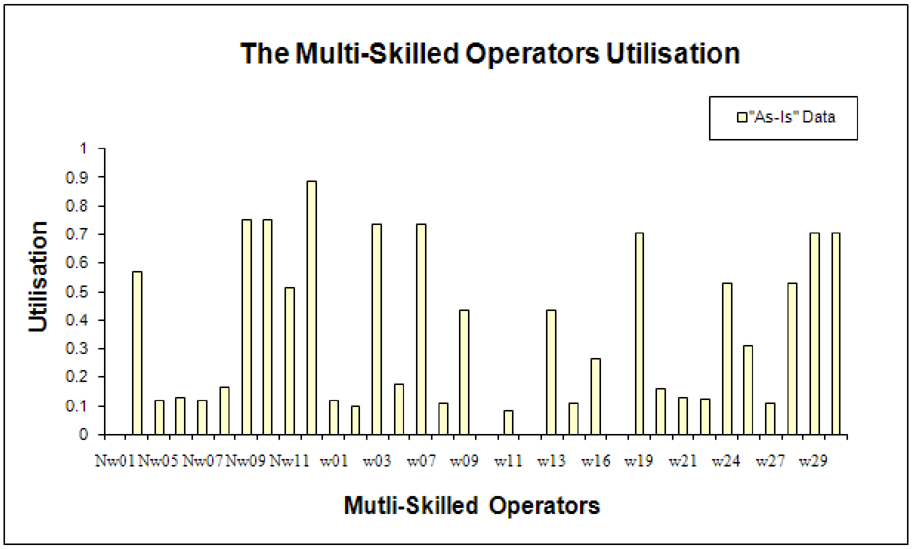


Figure 6.15: The multi-skilled operator utilisations

It can be concluded that some of the involved operators were well trained and had multi-skills which enabled them to accept responsibilities. Skills of this nature enabled operators to undertake jobs in a number of production processes with less guidance from high-skilled workers.

Low multi-skilled operator utilisation, reveals that some operators were brought from other manufacturing sections to provide help and support in a particular portion of overall production process. These multi-skilled operators might be involved in carrying out jobs in other production sections responding to the requirement to apply their skills to any manufacturing section. Hence the low utilisation of some multi-skilled operators does not mean they are less utilised than others.

The required skilled balance to achieve the current allocation cost was necessary to identify average utilisation of skilled chargehand and operators in both shifts. Figure 6.16 shows the balance between multi-skilled chargehands and operators by adopting ‘As-Is’ allocation plan.

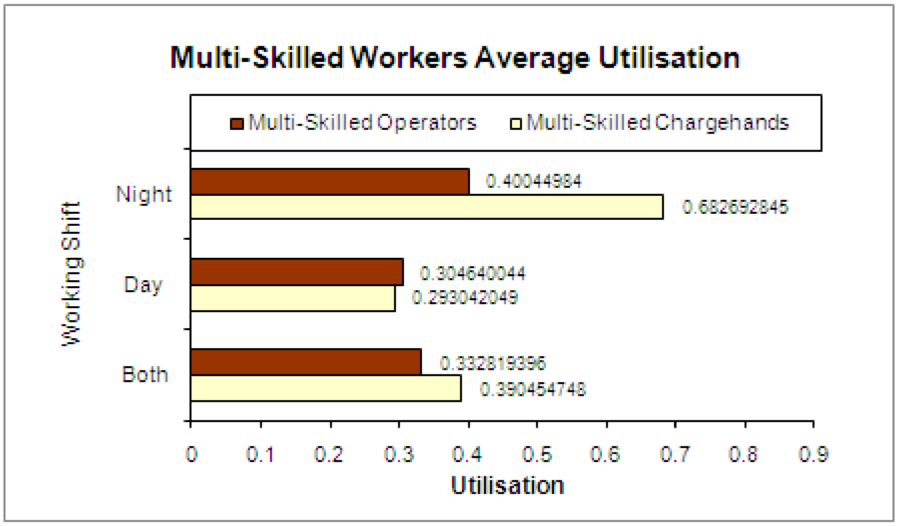


Figure 6.16: Balance of chargehand and operator utilisations

The utilisation rate of night shift multi-skilled operators is higher than day shift one because the "As-Is" allocation plan assigned a smaller number of operators compared with chargehands. The average utilisation of day shift operators was calculated by also considering those not involved (operators with zero utilisation rates such as w25, w27, w29, and w30 are used elsewhere in other production sections).

To consider the effects of sharing operators among processes on average process waiting time and average waiting time of each production section was calculated. Setup, cast and sawoff processes show a high waiting time because of sharing workers amongst assigned crews on those processes. See figure 6.17 for average process-waiting times at production section 1

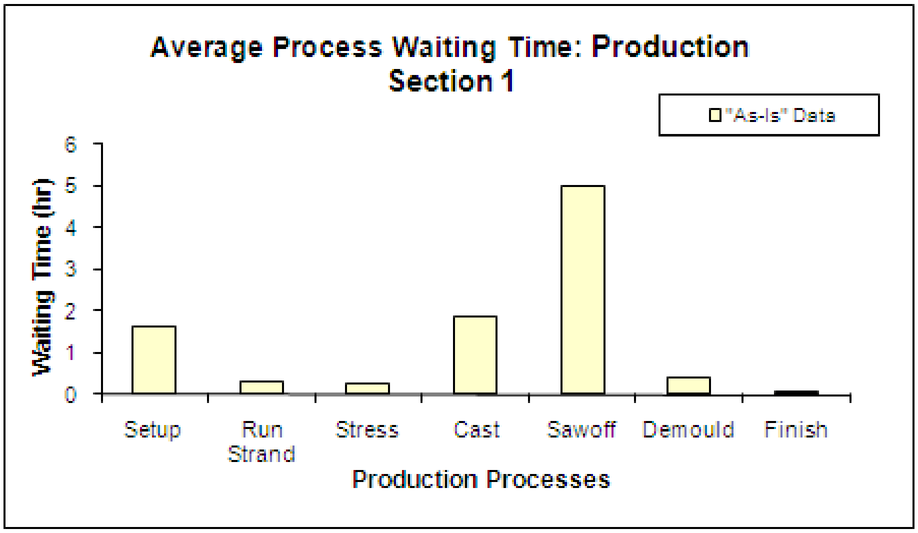


Figure 6.17: The average process waiting time of production section 1: "As-Is" scenario

This type of delay can cause process-waiting time as a process is delayed until a complete crew compliment available and ready to be assigned to a process. In figure 6.17, the setup process is the first production process for both production lines in which sharing, workers can cause a process waiting time for one of them. The casting process suffers from waiting time caused by using shared mixer and a shared casting machine which can be busy in providing concrete to more than one place in the same section.

After the curing process, both moulds are ready to be sawn off and because of the use of a shared sawoff machine, a higher waiting time results. Less waiting time is noticed in run strand, stress, demould, and finish processes as they need a smaller number of workers and they take less processing time.

In production section 2, process times are much longer than production section 1 because section 2 is used to produce special types of products and only one working shift is adopted. Each production process needs a greater number of operators and a longer process time to carry out the required job within one working shift. See figure 6.18

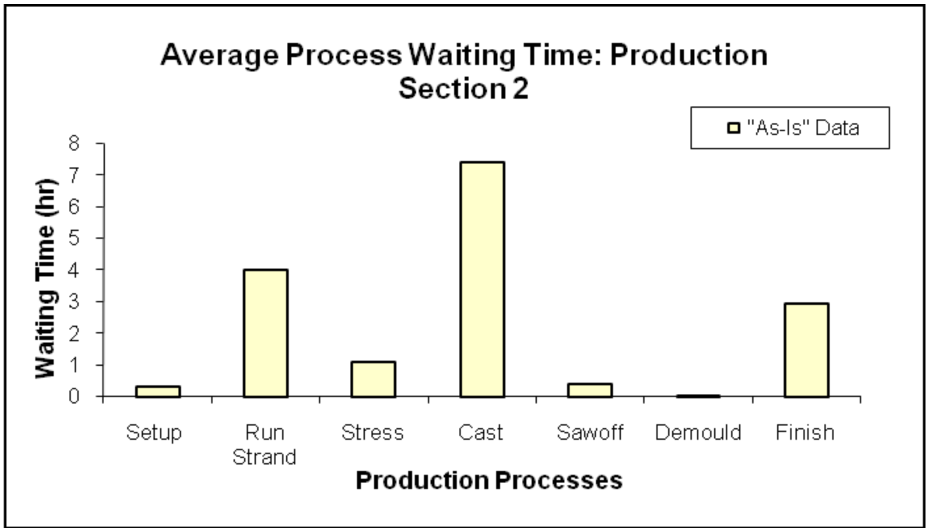


Figure 6.18: The average process waiting time of production section 2: "As-Is" scenario

In figure 6.18, higher average waiting times in both run strand and cast processes can be identified. The reason behind the run strand waiting time was that line 2, in production section 2, was waiting for a number of production processes to be finished elsewhere using the shared workers required to run strand in line 2.

The reason for the resultant high waiting time in casting process was caused as a large number of skilled chargehands and operators were required to carry out the activities involved in this process and hence the probability of sharing some of them in other processes is high.

6.9 VISUALISATION

6.9.1 2D-Visulisation of the Precast Labour-Intensive Manufacturing System

The visualisation of the sleeper precast manufacturing system is shown in figure 6.19. Each production process was visualised using the animation constructs available in ARENA software.

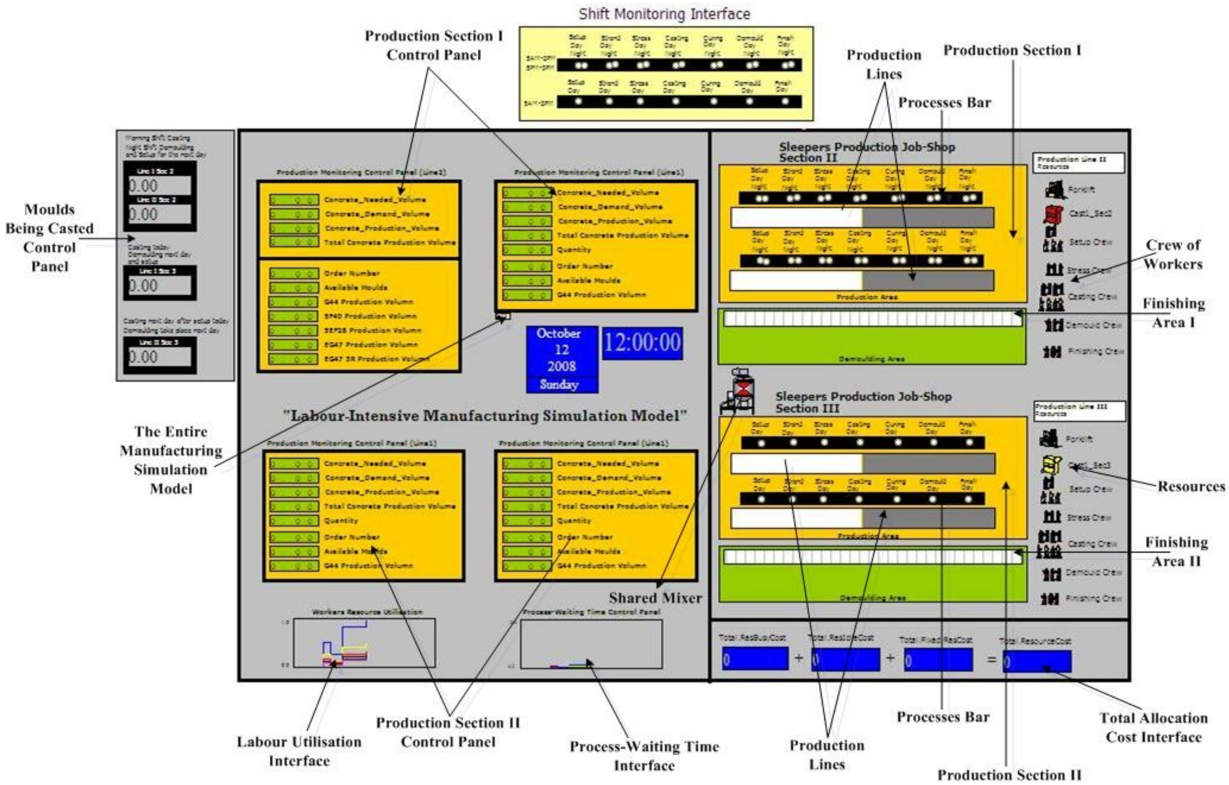


Figure 6.19: Depicts the simulation of casting process

The visualisation above shows the animation of each production section, both production lines of each production section, the shared mixer and vehicles that are used to move out the final product to the open stockyard area. The progress of each process was animated to follow the progress of each process. Monitoring interfaces were developed in order to present the current amount of production, demand, required concrete quantity, and other statistics. The utilisation rate of each labourer is shown graphically; the costs of using labour were animated using animation boxes. Each mould was animated to indicate the filling process of concrete. A level bar was used to show the process of filling a mould with concrete.

6.9.2 Development of a 3D-Simulation Model

The value of 3D visualisation model of the sleeper precast manufacturing system was considered as a confirmation tool. This visualisation was vital to convince the production manager of the performance of the current applied allocation plan. Four performance criteria (allocation cost, throughput time, resource utilisation and process-waiting time) alongside the 3D environment drove the production manager to be more cooperative in terms of providing feedback about the simulated model and suggesting a number of alternative allocation plans.

The development of the 3D simulation model to imitate the sleeper precast production system starts with identifying the logic of processes in such production system. Figure 6.20 shows the development steps of the 3D precast simulation model.

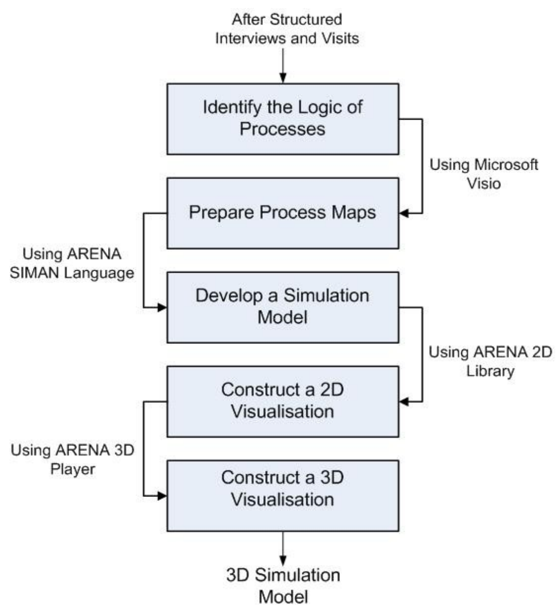


Figure 6.20: Development steps of the 3D precast simulation model

In figure 6.20, the simulation process was started by translating the developed logic of the process to a dynamic simulation model. ARENA SIMAN language was used to enable such a translation adopting the Discrete Event Simulation (DES) concept. The resulting model was presented in terms of simulation blocks linked with each other (by links). Those blocks involve decision, process, assign and other useful modelling blocks.

The visualisation of simulation model started with using the available 2D icons in the 2D simulation library. Such animation gives a 2D representation of the sleeper manufacturing system being investigated identifies whether/ or not the simulation model is successful in imitating the real system.

The 3D-visualisation is an advanced modelling system in which the user and other production planners can show the imitation of the manufacturing system being simulated in terms of 3D aspect. This 3D aspects was useful to provide a navigation tool that enabled users or production managers to explore the virtual model's components and see whether it was successful in representing the real world system or not.

ARENA 3D player developed by Rockwell Automation Company was used to enable such advanced visualisation. In addition, a dashboard in which all performance criteria were included was developed to be presented with the 3D-visualisation. The main functionality of this dashboard was to reflect the system's performance and efficiency whilst running different crew allocation plans.

- **3D Visualisation of the Precast Labour-Intensive Manufacturing System**

Arena 3D-Player was used to visualise sleeper precast labour-driven processes in the manufacturing system being investigated in terms of 3D simulation. 3D simulation can be used in all these steps as a communication tool to convey the idea of how a production system works and how it performs to avoid costly mistakes, as early as possible, Anttila (2005).

The purpose of this type of visualisation was to provide the production planners, managers and top level management with more advanced visual facilities. Then, the decision making process was made easier after considering what is happing in their production facility by running different scenarios. For the simulation analyst, it was also clearer from the 3D-visualisation whether the simulated logic is moving on the right direction or not. See figure 6.21

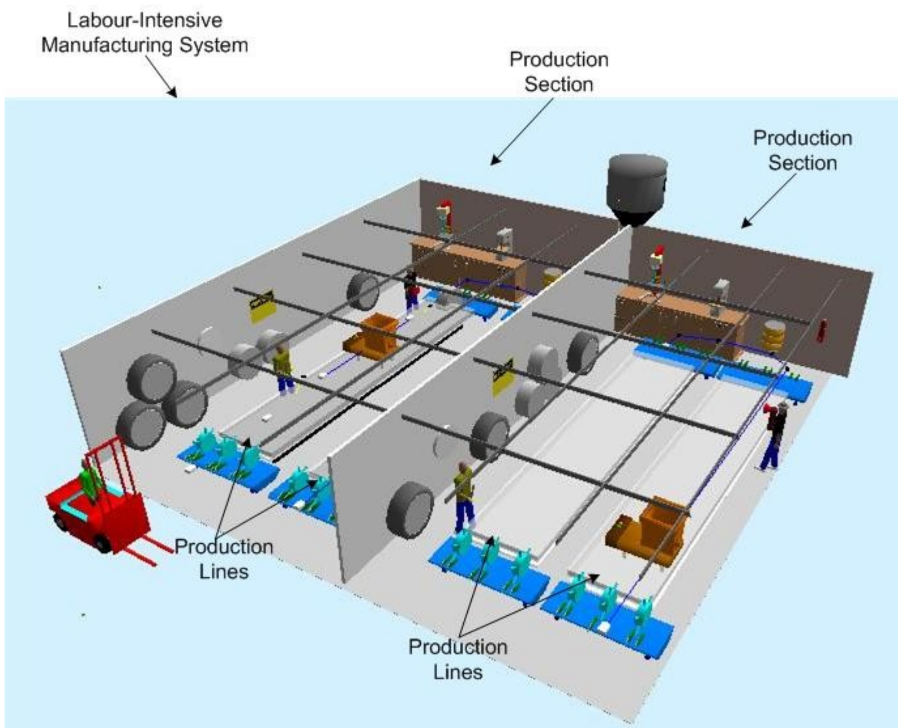


Figure 6.21: Snapshot of the sleeper manufacturing system

After developing the simulation model using Arena 12 (the 2D simulation model presented in subsection 6.3.1), a playback file generated from Arena provided extra information such as Arena object names to Arena 3DPlayer. See figure 6.22 for the visualised resources

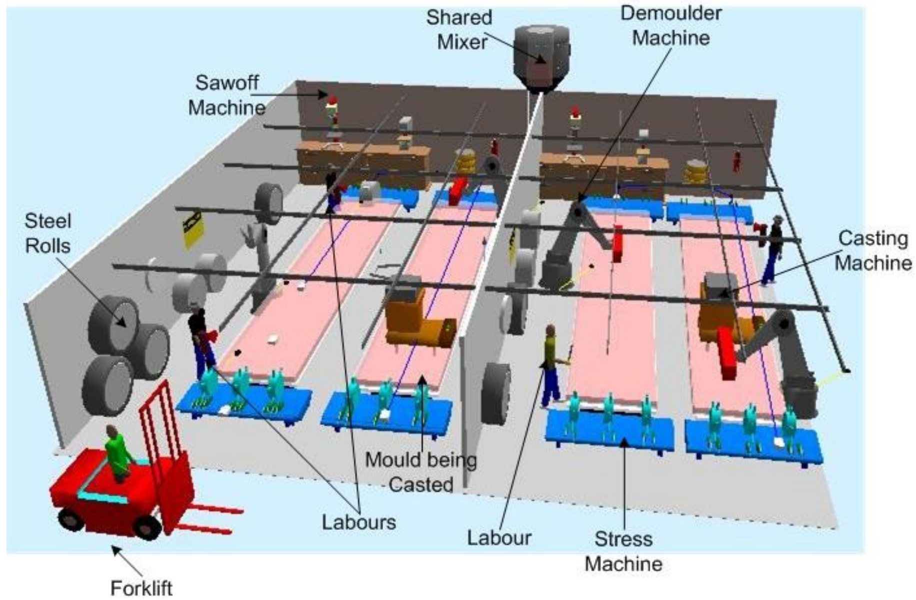


Figure 6.22: Snapshot of the visualised resources

In figure 6.22, all shared resources such as casting machines, run strand wire car and stress machine were visualised to show how such productive resources can be shared to carry out processes. In addition, a number of worker crews was animated to show the current flow of work. This animation was useful in verifying the simulation model with the production planner.

6.10 CHAPTER SUMMARY

This chapter discussed the development of a simulation model for the sleeper manufacturing system. While developing the simulation model, the researcher faced a number of software limitations concerning the schedule process of resources. The model was validated to ensure a good representation of the current production plan. The results from the simulation were close to the real situation. The comparison between the simulated results and the real case results such as production cycle time, the time that each production line takes to produce one mould of concrete showed that the simulation model was acting and working exactly as the real case.

As the research was initiated to achieve the best allocation of crews of workers to production processes, the model was first developed to imitate "As-Is" situation, then the developed model was coupled with an optimisation module for more improvement.

The simulation model was verified to ensure that the developed model behaved in the "As-Is" way. The development of an optimisation module will be discussed in detail, in the next chapter.

CHAPTER 7

DEVELOPMENT OF THE CREW ALLOCATION OPTIMISATION MODULE

7.1 INTRODUCTION

A large number of analytical assignment models have been developed to solve the allocation problems during the last 50 years (Pentico, 2007). Most of real life allocation problems are complex and a large number of alternatives have to be modelled: this kind of alternatives explosion causes combinatorial problems. To avoid the problem of a 'combinatorial explosion', heuristic rules and artificial intelligence tools have been developed to solve allocation problems in real life systems.

As one of the artificial intelligence techniques, the Genetic Algorithm (GA) can be used as a standard optimisation technique with any simulation model (Paul and Chanev, 1998). In addition, the GA can be considered as an integrated iterative technique with simulation to ensure that a solution is feasible for real world operations (Bush et. al, 2003).

The purpose of developing an optimisation module for the allocation process is to generate and investigate more possible crew allocation plans, for a better performance. In this chapter, further details concerning the development of multi-layered genetic algorithms, are discussed. An algorithm of generating initial population using Monte-Carlo sampling is presented. The core of the developed optimisation engine is demonstrated. The logic of generating new iterations in terms of flowchart is developed in order to provide an idea about how populations can be evolved generation by generation. A mechanism of accommodating a chromosome into a multi-layered structure is introduced. A special rule called 'one search' is presented to avoid the proposition of similar allocation plans.

The development of a suitable interactive interface for the allocation system is demonstrated; other report files required in the verification and validation process are presented. In order to compare the developed algorithm with other possible searching algorithms, Monte Carlo simulation and Simulated Annealing models were developed to prove the performance of the proposed model in terms of solution optimality and efficiency.

7.2 INTEGRATION OF OPTIMISATION MODULE WITH THE SIMULATION MODEL

Genetic Algorithms are defined as computational models, simulating the process of genetic selection and natural elimination in biological evolution. They are one of the most promising meta-heuristics algorithms (Alcaraz and Maroto 2001).

After simulating the current allocation situation, it was noted that both high allocation cost and waiting times of a number of processes still needed to be minimised and hence the simulation modelling alone was not enough to solve the problem. The management believed that an inappropriate allocation of skilled workers might result in high labour allocation costs, and it was known that resource utilisation and process-waiting time were associated with this type of the allocation plan. However, optimisation was introduced as one of the possible sophisticated solutions that could improve the current situation by testing other alternative allocation plans.

In this work, the Genetic Algorithm model was designed to be coupled with process-simulation model for further guidance of the simulation model toward choosing the best processing crew among set of possible crew alternatives. The reason behind choosing a

GA was its ability to intelligently search through a solution space (see chapter 2, section 2.3.7). In the crew allocation problem that was being studied, an intelligent searching algorithm was developed to investigate large pool of crews and to decide which set of crews can be allocated to labour-driven processes in order to minimise labour costs. See figure 7.1 for the simulation optimisation process.

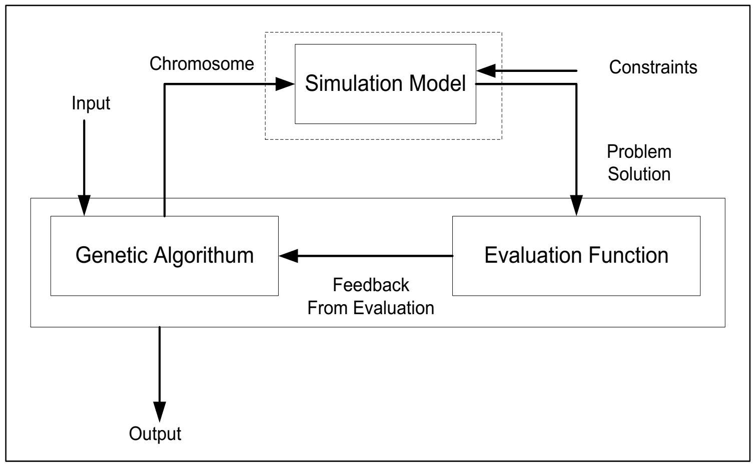


Figure 7.1: Simulation optimisation process (modified from Chan and Hu 2002)

In figure 7.1, the optimisation procedure used the outputs from the simulation model which evaluated the outcomes of the inputs that were fed into the model, in order to derive a new set of input variable values. The simulation program procedure continued iteratively until the algorithm stopped, having either found the optimal or satisfied a stopping rule, or reached a predetermined period of time. However, Genetic Algorithms provide an initial set of inputs and uses the responses generated by the simulation model to make decisions regarding the selection of the next trail solution.

7.3 DEVELOPMENT OF THE CREW ALLOCATION SEARCHING ENGINE

In this section, a number of flowcharts and algorithms used in the development of the searching engine are presented: Generation of the initial solution, generating the next generation (defined as the mechanism used to move on a further generation, Davis

1991), accommodating a chromosome into a multi-layered structure, the 'one search' strategy used to avoid solution duplications, the optimisation engine and how its component work, and searching for a gene in a multi-layered chromosome. The generation of initial solution was developed to provide good starting condition:

7.3.1 Algorithm for Generating Initial Population of Crews' Indices

An initial solution should be available as a starting point to enable the optimisation engine to evolve the initial solution towards an optimal one. To obtain a Multi-Layered initial random solution, the Monte Carlo Sampling technique was used to generate a crew index for each process at each layer. A uniform random number generator was used to generate the crew indices. The reason of adopting such a distribution was to provide an equal chance of selecting any possible crew of workers to a process. As each process has a pool of alternatives (explained in chapter 4, section 5) and because that pool is stored in a database, the initial solution was generated using VBA codes and the resulting random numbers which represent crew indices were stored in the database for better processing. The developed algorithm to generate an initial starting solution is shown as follows:

```
Open Access Database
Delete all crews' indices from the population pool table
        For each Process
                For each Shift
                Determine number of crew alternatives available (for each process
                 at each shift)
                        For each chromosome
                        Generate crew index using Monte Carlo Sampling (does
                        not exceed maximum number of alternatives for each process at each shift)
                        Store in the population of indices pool table
                        End
                End
        End
Close Access Database
```

The range of random numbers for each gene can be determined using the following constraint

$$MinCA_i \leq R_i \leq MaxCA_i \qquad \text{…. (7.1)}$$

where:

R_i is an integer random number for each chromosome i

$MinCA_i$ is minimum number of crews alternative in gene i and

$MaxCA_i$ is maximum number of crews alternative in gene i

Chromosome structure plays a vital role in converting crew index to the actual crew; the generated decimal random numbers are matched up with each crew position in the pool to call the desired crew of workers.

7.3.2 Generating the Next Generation

To evolve the resultant solutions after applying the 'SIM_Crew' allocation system, more than one generation was required to investigate the solution space. A number of generations were required to extensively search the solution space for an optimal or near optimal solution.

The generating of the 'next generation' was an important step to provide the searching engine with more promising chromosomes for further investigation. Any generation should involve promising chromosomes that have good characteristics inherited from previous chromosome generation. See figure 7.2 for the next generation algorithm

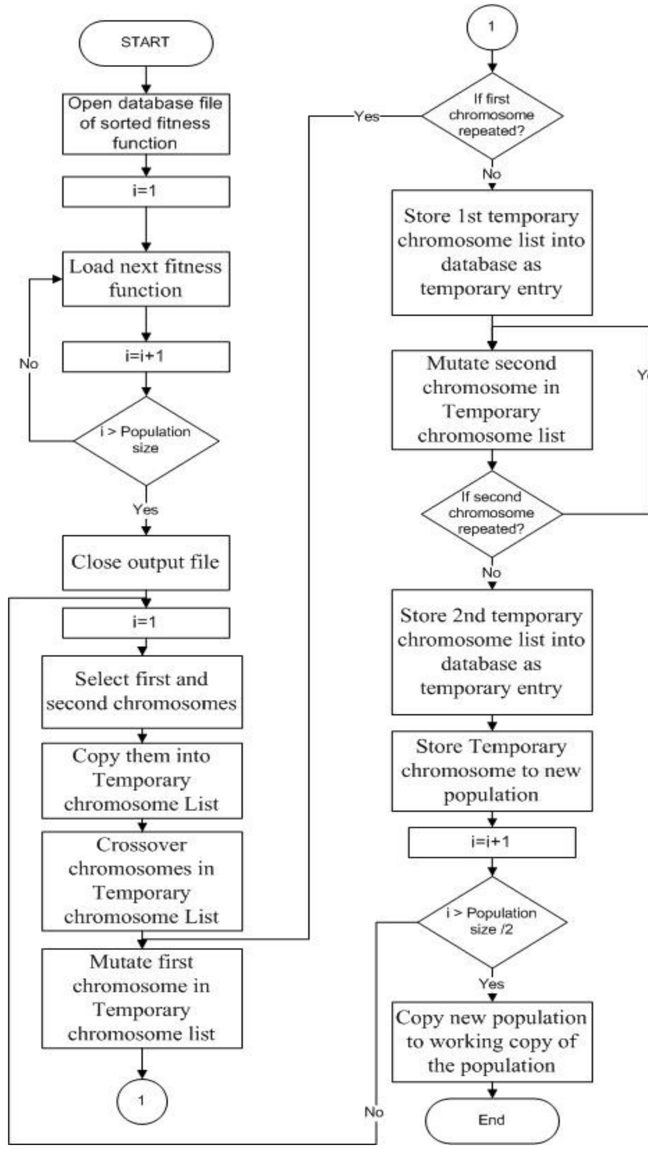


Figure 7.2: Flowchart of generating new generations

The generation of a new generation is a major step towards suggesting more promising solutions in the evaluation process. The generation process is achieved by opening database files with a sorted fitness function in descending order, then loading the next fitness function for all population sizes.

The selection of chromosomes was done by using a 'Class Interval' strategy which depends on the individual selection of each pair of chromosomes. After the selection of each pair of chromosomes, each pair was copied to a temporary chromosome list for memory purposes. Crossover for a pair of chromosomes was done using a dynamic probabilistic rule; the selection of genes to be crossed-over during the crossover process was explained earlier in chapter 3, section 6.1.3.

For the mutation process, the first chromosome was selected, and then gene/genes from that chromosome were mutated as described earlier in chapter 3, section 6.1.3. If the mutated chromosome was repeated then mutation was continued until a unique chromosome was obtained. This unique chromosome was copied as a temporary chromosome into the main population database. This was useful in determining unique chromosomes. These chromosomes were be given a (-1) generation number to distinguish them later during the discarding process.

The same procedure was applied to the second chromosome to determine the second unique chromosome. This process continued until the requisite number of paired chromosomes was satisfied. All unique chromosomes were then copied to the VBA database (ARENA 3D Array) and discarded from the main chromosomes population Access database. The ARENA 3D Array is explained in the following section:

7.3.3 Accommodating a Chromosome into a Multi-Layered Structure

Any resulted chromosome by the optimisation engine was presented in terms of a string and stored into an 'output summary' table in the Access database explained in chapter 5, section 2.2. In order to generate a new generation and because of the Genetic Algorithm operators were run using the coded optimisation engine inside the ARENA VBA editor, all chromosomes' strings were needed to be placed and sorted into three dimensional ARENA array. Visual Basic for Applications (VBA) exploited all integration capabilities of automation and it run within the application. VBA is similar to other Microsoft programming languages included in desktop applications that support ActiveX Automation. See figure 7.3 for the developed three dimensional ARENA array.

The form of the three dimensional ARENA array is represented as:

Chromo (process ID, Crew ID, Shift ID)

Where

Chromo is the chromosome array name.

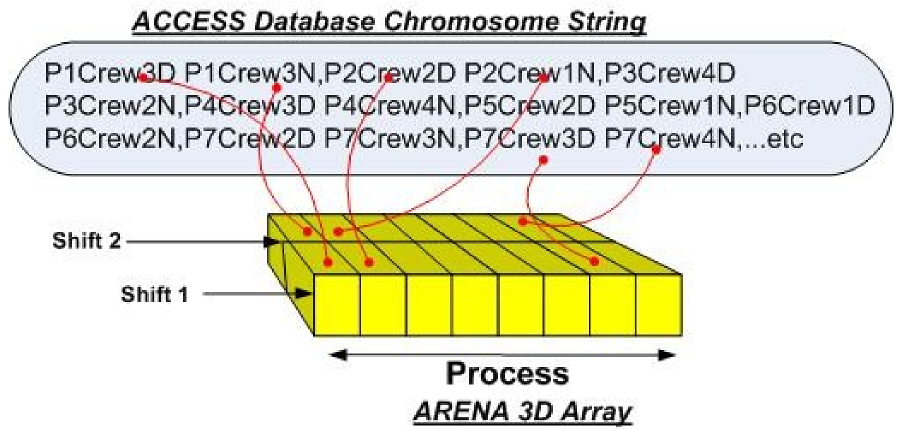


Figure 7.3: Accommodating a chromosome into three dimensional ARENA array

In figure 7.3, each crew of a process, according to its shift pattern is stored into three dimensional ARENA array. To do so, each space here is considered as a changing of shift and each comma considered as a beginning of a new process. Visual Basic for Application (VBA) subroutines were developed to process data exchange between the three dimensional ARENA array and Access database files. The database was designed in a way that process, crew, and worker could be added very easily to the database.

The embedded Visual Basic for Application (VBA) language was used to generate the entire Arena experiment frame and animation displays for a large number of very complex simulation models (Seppanen, 2000). In order to code the proposed optimisation algorithm, VBA supporting language was used to code the logic mentioned in the developed algorithm. These codes can control the modules used in the developed simulation model for more control and guidance. VBA was used to link ARENA with Access database in order to save and retrieve information. VBA codes were written to generate the entire ARENA experiments frame. See figure 7.4 for the VBA window

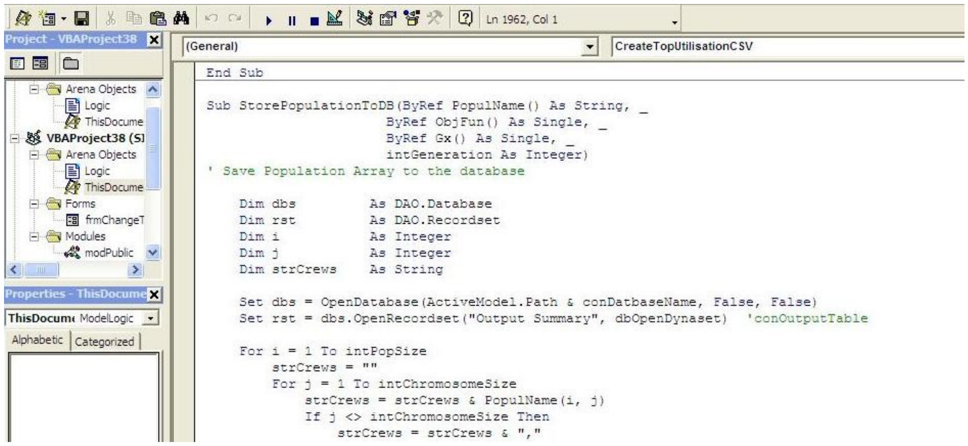


Figure 7.4: VBA codes written for ‘SIM_Crew’ System

Figure 7.4 shows the VBA codes developed to read data from the Access database to be fed into the simulation engine. In addition, optimisation module codes were written to be executed each time the simulation was run in order to provide the simulation model with a different set of crews to be allocated on its processes. Arena’s standard ActiveX and DAO interfaces and VBA, corporate data can be incorporated directly into the simulation model (Bapat and Sturrock 2003). VBA codes were written to design the output of verification and validation text files. Many constraints were coded using VBA to avoid Chromosome Duplication:

7.3.4 Avoiding Chromosome Duplication

As solutions (chromosomes) were generated randomly using the Genetic Algorithms operators, the possibility of repeated solution existed. Such repetition causes extra calculations and subsequently leads to increasing time and calculation operations. In order to avoid duplication of chromosomes while evaluating chromosomes and to minimise evaluation time and calculation operations; one search strategy was developed to search for any duplications and to discard any repeated chromosomes. This enabled the ‘SIM_Crew’ engine to evaluate just non-duplicated chromosomes to enable faster and better investigation.

‘One Search’ strategy enables investigating the current generation chromosome to check whether any chromosome was repeated in the chromosome list, which was stored in Access database, or not.

The non-repeated chromosomes were stored temporarily in the chromosomes access database under generation number equal to (-1). Defining chromosomes with (-1) as a generation number for the non-duplicate chromosomes to enable the discarding of them after copying of them to the VBA database. Figure 7.5 below shows the one-search strategy steps that ‘SIM_Crew’ applied to filter the resulted chromosomes.

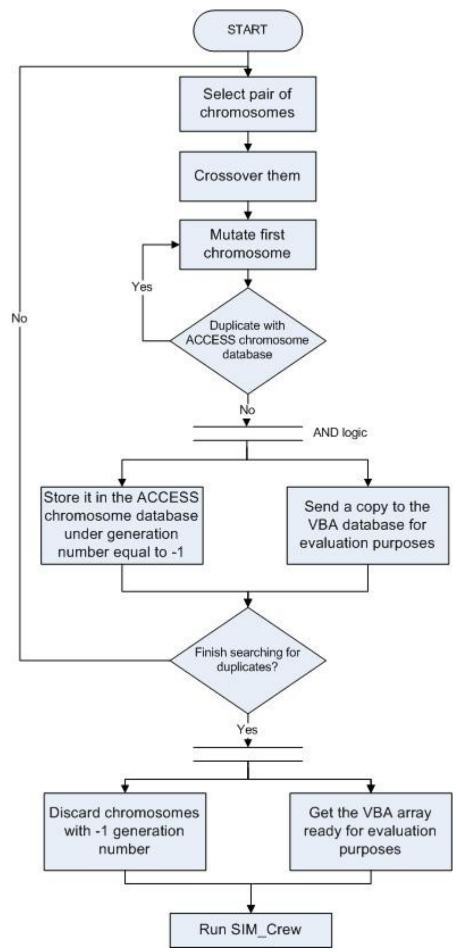


Figure 7.5: ‘One Search’ strategy flowchart for duplication

In the developed flowchart, ‘one search’ strategy was developed to save computation time and program codes. In ‘one search’ strategy and after selecting a pair of chromosomes, crossover took place by swapping selected genes using the probabilistic dynamic strategy. To add more randomness to the crossed-over chromosomes, each chromosome should be mutated individually with its available list of alternatives for each process using Monte Carlo (MC) sampling method. The mutated chromosome was checked with the Access database which involves all chromosomes generated for all previous populations (populations’ history), then if the tested chromosome was duplicated, mutation process could continue until a unique chromosome was obtained.

After finding a unique chromosome, a copy of this chromosome was sent to the Access database ‘population list’ under generation number equal to (-1) and another copy to the VBA array. The VBA array involves all unique chromosomes for the current generation for evaluation purposes. After testing all chromosomes for duplication, all chromosomes having a generation number equal to (-1) could be discarded from the Access database population history and VBA array was then ready to be fed to the simulation engine for evaluation purposes.

The purpose of the temporary chromosome was to help check for duplicated entries while the next generation was being created. As each chromosome was generated through crossover mutation operators, it was stored into the database with a generation number equal to (-1), -1 being a flag that aids the deletion of non-repeated chromosomes. This means that all past, current and proposed chromosomes are held in one location therefore, a single search, could check to see if the new chromosome was a duplicate chromosome.

The one search strategy ensured that all chromosomes should be unique before evaluating them; therefore, there was no point to test for repeated chromosomes, as it wasted time and computational effort was required.

7.3.5 Crew Allocation Optimisation Engine

The proposed optimisation engine was incorporated with the simulation to form a kind of hybrid system. This type of integration provided the facility for proposing allocation plans by the optimisation engine and testing them via the simulation model as an evaluation tool.

The optimisation engine developed here is based on an intelligent searching algorithm that enables the finding of a good solution and discarding weak and trivial solutions. See figure 7.6 for flowchart of the optimisation engine

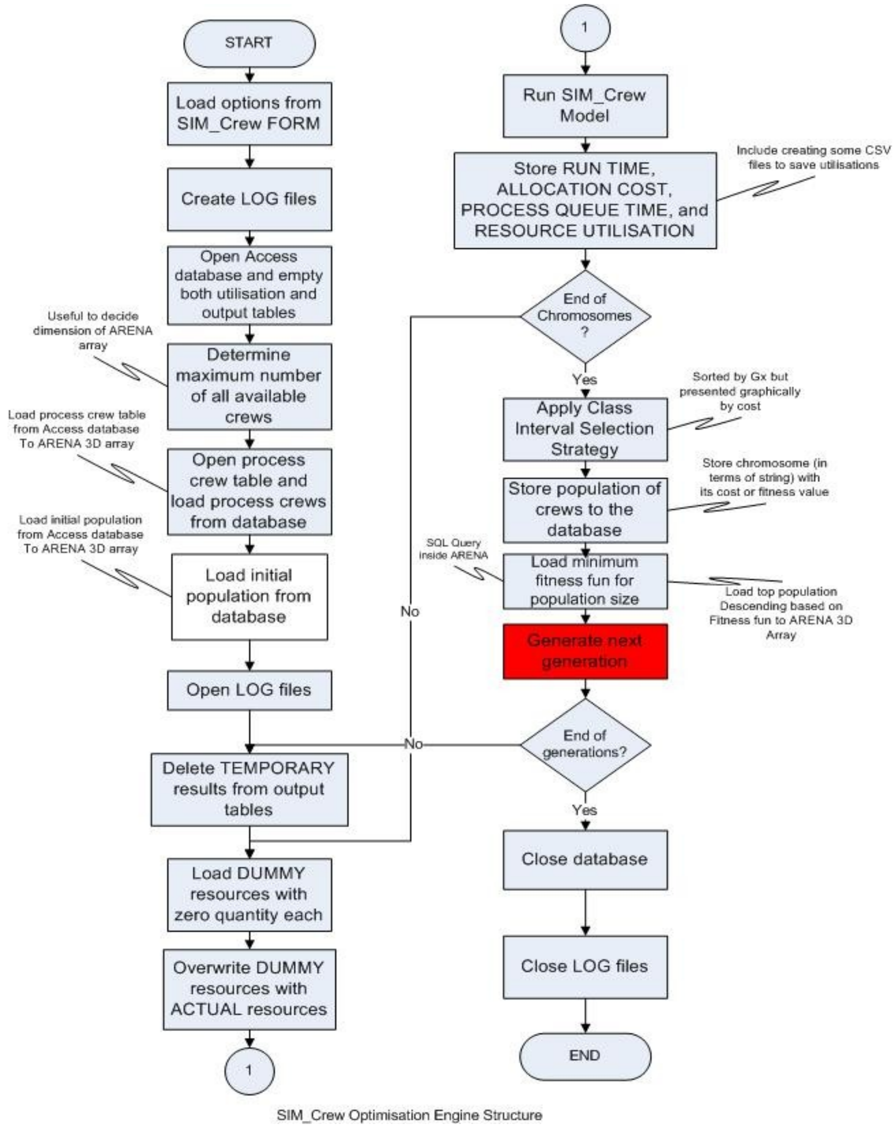


Figure 7.6: Flowchart of the optimisation engine

In the figure 7.6, the creation of LOG files was the first step in the optimisation engine flowchart as LOG files are useful and necessary to determine what is happing inside the optimisation engine and how crossover and mutation operators work. Reset all database files was used to obtain the database files ready to accommodate new results.

Determination of the maximum number of crew alternatives available for each process was important to provide the number of available crews of each process to enable further evaluation (explained in section 7.3.1). Loading process crews from the database to the memory was required to ensure crews were ready for allocation.

The initial population of chromosomes (each chromosome consists of a set of crews to be assigned to processes), each set of crews was randomly generated using a Monte Carlo sampling technique. The maximum number of alternatives available for each process was useful in determining the upper boundary of each random number to be generated for each process, as a coded population. After preparing the LOG files, these files were opened and made ready to accommodate any outputs. After resetting and initialising all database files, DUMMY resources were placed into the process block template as initial resources were required for process templates before any changing occurred. This limitation of the process template module was overcame by placing DUMMY resources with zero quantity of each just as names, and then real resources could replace the DUMMIES by overwriting over them with capacities equal to one.

The maximum number of resources needed to carry out a process was determined to give a maximum number of DUMMIES needed for each process. After running the simulation model for all chromosomes, all results in terms of throughput times, allocation costs, process queuing times and resource utilisation were stored into a database for further generation.

To avoid chromosome duplication it was necessary to discard any repeated chromosomes used to shorten the time of searching, besides saving time and searching efforts. After developing a new generation (explained in section 7.3.2) and after satisfying a certain number of generations, all LOG file and database files needed to be closed to plot the outputs and start analysing and interpreting the outputs. As a part of modelling of the optimisation module, the creation process of ARENA 3D array (explained in section 7.3.3) was considered. A number of technical requirements such as avoiding chromosome duplication, and searching for a gene in multi-layered chromosome were addressed.

7.3.6 Searching for a Gene in a Multi-Layered Chromosome

For the multi-layer chromosome, all genes had given sequential numbers, starting from 1 to the number of the last gene in the n layer of the chromosome. See figure 7.7 for the searching process in a multi-layered chromosome

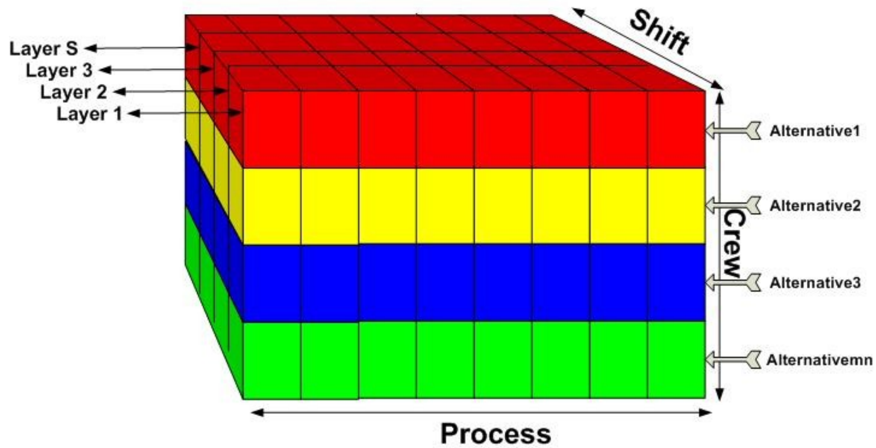


Figure 7.7: Searching for a gene in a multi-layer structure

In order to have less parameters to pass and for easier comparison, a mathematical formula was derived to search for the required gene through n layers of the chromosome being crossed-over or mutated. The formula is expressed below:

$$GenePosition = (\text{Shift Number} - 1) \times \text{Chromsome Size} +$$

Where:

i : Process number index

The mixing between the designed multi-layered structure and this searching strategy can provide advanced searching for a gene through n layers of the chromosome. There are other ways of achieving this but they were considered as computationally expensive. For example, if the selected gene is in the second shift, process 4, then the gene number is:

*Gene position= (2-1)*28+4= 32,* where 32 is the selected gene number in the second layer (shift 2)

7.4 VERIFICATION OF THE OPTIMISATION MODULE

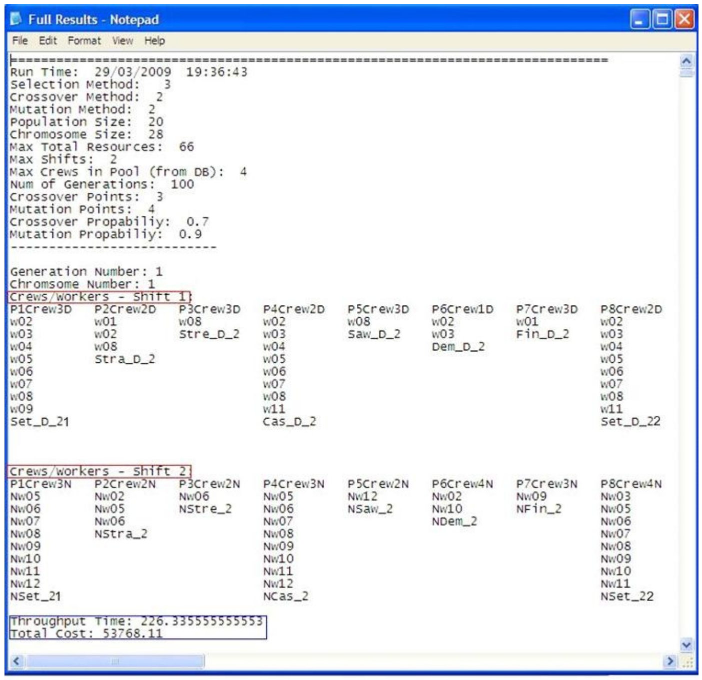
To verify the developed optimisation modules, text (LOG) files were created to show visually, the outputs of the GA operators. Each chromosome at each generation was tracked and checked before feeding it to the simulation model as a feasible solution.

Three text files were designed using VBA; one to show labour inputs loaded from the Access database beside the outcome of the allocation plan, in terms of throughput time, and total allocation cost. The second text file showed how the selection operator 'class interval' works. The third one verified both crossover and mutation operators.

The verification of the proposed operators was important to check on whether the coded algorithm was working as planned, or not. All these files were designed to show the solution progress generation by generation.

7.4.1 Database Integration Verification LOG File

The main advantage of the LOG file was to verify whether the integration with the Access database was successful, or not. In addition, it showed full allocation plan details and the outcome of them. See figure 7.8 for the database integration verification outputs



```
Full Results - Notepad
File  Edit  Format  View  Help
===============================================================================
Run Time:  29/03/2009  19:36:43
Selection Method:   3
Crossover Method:  2
Mutation Method:  2
Population Size:  20
Chromosome Size:  28
Max Total Resources:  66
Max Shifts:  2
Max Crews in Pool (from DB):  4
Num of Generations:  100
Crossover Points:  3
Mutation Points:  4
Crossover Propabiliy:  0.7
Mutation Propabiliy:  0.9
---------------------------

Generation Number: 1
Chromsome Number: 1
Crews/Workers - Shift 1:
P1Crew3D   P2Crew2D   P3Crew3D   P4Crew2D   P5Crew3D   P6Crew1D   P7Crew3D   P8Crew2D
w02        w01        w08        w02        w08        w02        w01        w02
w03        w02        Stre_D_2   w03        Saw_D_2    w03        Fin_D_2    w03
w04        w08                   w04                   Dem_D_2               w04
w05        Stra_D_2              w05                                         w05
w06                              w06                                         w06
w07                              w07                                         w07
w08                              w08                                         w08
w09                              w11                                         w11
Set_D_21                         Cas_D_2                                     Set_D_22


Crews/Workers - Shift 2:
P1Crew3N   P2Crew2N   P3Crew2N   P4Crew3N   P5Crew2N   P6Crew4N   P7Crew3N   P8Crew4N
Nw05       Nw02       Nw06       Nw05       Nw12       Nw02       Nw09       Nw03
Nw06       Nw05       NStre_2    Nw06       NSaw_2     Nw10       NFin_2     Nw05
Nw07       Nw06                  Nw07                  NDem_2                Nw06
Nw08       NStra_2               Nw08                                        Nw07
Nw09                             Nw09                                        Nw08
Nw10                             Nw10                                        Nw09
Nw11                             Nw11                                        Nw10
Nw12                             Nw12                                        Nw11
NSet_21                          NCas_2                                      NSet_22

Throughput Time: 226.335555555553
Total Cost: 53768.11
```

Figure 7.8: Snapshot of the database integration verification

In figure 7.8, P1Crew3D means that process 1 has crew 3 allocated on during day shift time. The formation of each crew of workers was categorised into two categories: day and night shift. The crew formation of each process at each shift were visualised in detail. Allocation cost and throughput time were presented with each allocation plan.

7.4.2 'Class Interval' Verification LOG File

This LOG file was developed to check the functionality of the GA operators. Selection, Crossover, and Mutation rules were followed step by step to check on whether the coded operators were working as planned, or not. See figure 7.9 for the high-level validation file output

Class Interval Selection Rule.txt - Notepad

File Edit Format View Help

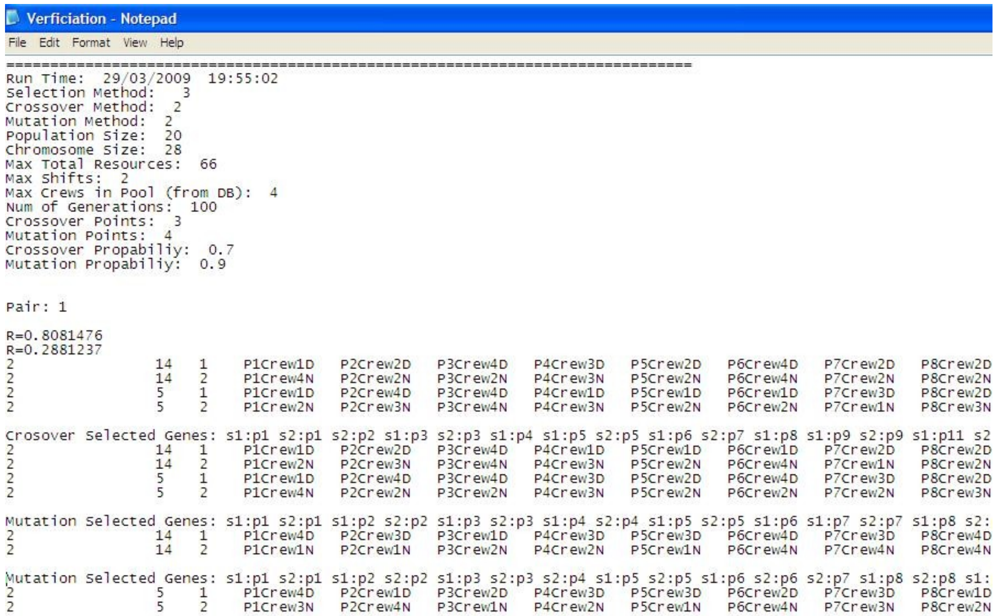
Gen	Gene	ObjFun	Gx	SortGene	SortedGx	RelGx	CumRelGx	Intervals
15	1	51312.62	4998.84	2	6930.211	0.09731	0.1	0 - 0.09
15	3	51085.4	5226.063	17	6297.242	0.08842	0.28	0.19 - 0.27
15	4	54071.72	2239.742	20	5453.281	0.07657	0.36	0.28 - 0.35
15	5	53130.38	3181.082	3	5226.063	0.07338	0.43	0.36 - 0.42
15	6	53925.65	2385.813	10	5226.063	0.07338	0.5	0.43 - 0.49
15	7	53552.36	2759.102	1	4998.84	0.07019	0.57	0.5 - 0.56
15	8	55629.8	681.6602	12	4722.93	0.06632	0.64	0.57 - 0.63
15	9	49624.7	6686.762	15	3943.891	0.05538	0.69	0.64 - 0.68
15	10	51085.4	5226.063	14	3440.762	0.04831	0.74	0.69 - 0.73
15	11	53000.54	3310.922	11	3310.922	0.04649	0.79	0.74 - 0.78
15	12	51588.53	4722.93	5	3181.082	0.04467	0.83	0.79 - 0.82
15	13	54039.26	2272.199	7	2759.102	0.03874	0.87	0.83 - 0.86
15	14	52870.7	3440.762	6	2385.813	0.0335	0.91	0.87 - 0.9
15	15	52367.57	3943.891	13	2272.199	0.03191	0.94	0.91 - 0.93
15	16	56311.46	0	4	2239.742	0.03145	0.97	0.94 - 0.96
15	17	50014.22	6297.242	18	1038.723	0.01459	0.98	0.97 - 0.97
15	18	55272.74	1038.723	8	681.6602	0.00957	0.99	0.98 - 0.98
15	19	55889.48	421.9805	19	421.9805	0.00593	1	0.99 - 0.99
15	20	50858.18	5453.281	16	0	0	1	1 - 1

Figure 7.9: Snapshot of the 'class interval' verification and validation text file

In figure 7.9, the sorted populations according to the fitness function are illustrated in column (sortedGx). The relative fitness function (RelGx) was calculated using equation (3.3). The cumulative relative fitness function (CumRelGx) was calculated using equation (3.4). The interval width was identified from the CumRelGx column.

7.4.3 Crossover and Mutation Verification LOG File

The crossover and mutation operators were visualised in detail as a further requirement of the verification and validation process of such operators. The developed verification file shows the associated amount of outputs and costs linked with each chromosome. See figure 7.10 for the crossover and mutation verification and validation LOG file.


```
Verficiation - Notepad
File Edit Format View Help
==============================================================================
Run Time:  29/03/2009  19:55:02
Selection Method:   3
Crossover Method:  2
Mutation Method:  2
Population Size:  20
Chromosome Size:  28
Max Total Resources:  66
Max Shifts:  2
Max Crews in Pool (from DB):  4
Num of Generations:  100
Crossover Points:  3
Mutation Points:  4
Crossover Propabiliy:  0.7
Mutation Propabiliy:  0.9


Pair: 1

R=0.8081476
R=0.2881237
2               14   1    P1Crew1D   P2Crew2D   P3Crew4D   P4Crew3D   P5Crew2D   P6Crew4D   P7Crew2D   P8Crew2D
2               14   2    P1Crew4N   P2Crew2N   P3Crew2N   P4Crew3N   P5Crew2N   P6Crew4N   P7Crew2N   P8Crew2N
2               5    1    P1Crew1D   P2Crew4D   P3Crew4D   P4Crew1D   P5Crew1D   P6Crew1D   P7Crew3D   P8Crew2D
2               5    2    P1Crew2N   P2Crew3N   P3Crew4N   P4Crew3N   P5Crew2N   P6Crew2N   P7Crew1N   P8Crew3N

Crosover Selected Genes: s1:p1 s2:p1 s2:p2 s1:p3 s2:p3 s1:p4 s1:p5 s2:p5 s1:p6 s2:p7 s1:p8 s1:p9 s2:p9 s1:p11 s2
2               14   1    P1Crew1D   P2Crew2D   P3Crew4D   P4Crew1D   P5Crew1D   P6Crew1D   P7Crew2D   P8Crew2D
2               14   2    P1Crew2N   P2Crew3N   P3Crew4N   P4Crew3N   P5Crew2N   P6Crew4N   P7Crew1N   P8Crew2N
2               5    1    P1Crew1D   P2Crew4D   P3Crew4D   P4Crew3D   P5Crew2D   P6Crew4D   P7Crew3D   P8Crew2D
2               5    2    P1Crew4N   P2Crew2N   P3Crew2N   P4Crew3N   P5Crew2N   P6Crew2N   P7Crew2N   P8Crew3N

Mutation Selected Genes: s1:p1 s2:p1 s1:p2 s2:p2 s1:p3 s2:p3 s1:p4 s2:p4 s1:p5 s2:p5 s1:p6 s1:p7 s2:p7 s1:p8 s2:
2               14   1    P1Crew4D   P2Crew3D   P3Crew1D   P4Crew3D   P5Crew3D   P6Crew4D   P7Crew3D   P8Crew4D
2               14   2    P1Crew1N   P2Crew1N   P3Crew2N   P4Crew2N   P5Crew1N   P6Crew4N   P7Crew4N   P8Crew4N

Mutation Selected Genes: s1:p1 s2:p1 s1:p2 s2:p2 s1:p3 s2:p3 s2:p4 s1:p5 s2:p5 s1:p6 s2:p6 s2:p7 s1:p8 s2:p8 s1:
2               5    1    P1Crew4D   P2Crew1D   P3Crew2D   P4Crew3D   P5Crew3D   P6Crew2D   P7Crew3D   P8Crew1D
2               5    2    P1Crew3N   P2Crew4N   P3Crew1N   P4Crew2N   P5Crew1N   P6Crew4N   P7Crew3N   P8Crew2N
```

Figure 7.10: Snapshot of both crossover and mutation verification

In this snapshot, s1:p1 and s2:p1 indicates that both crossover and mutation take place in shifts s1 and s2 for process 1. The indicator of s2:p2 means that only process 2 in the night shift is included in the crossover or the mutation operator. Each selected pair of chromosome for crossover and the individuals for mutation were visualised.

All the system definition in terms of selection method, population size, probability of crossing over and mutating genes was included with other definitions.

7.5 RUNNING OF THE OPTIMISATION MODULE

7.5.1 Interface for Running of 'SIM_Crew'

To interact with 'SIM_Crew' system, an interface was designed to include all parameters used when writing VBA codes. The designed form being used to control GA parameters, attempt different GA operators, import files from integrated databases, and select the mode of output files. See figure 7.11 for 'SIM_Crew' designed interface

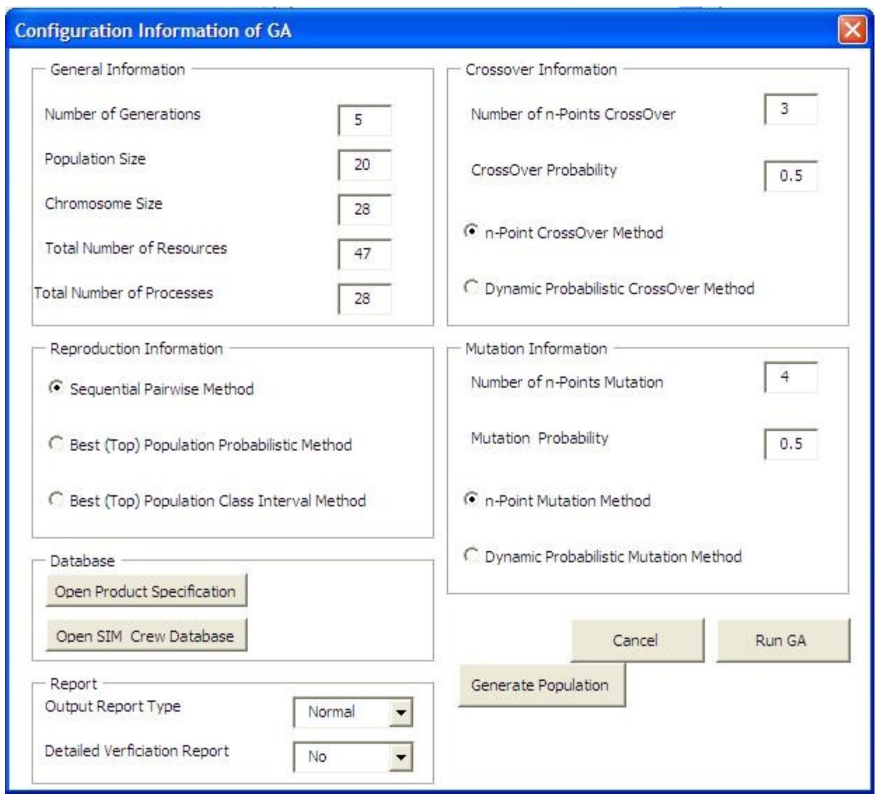


Figure 7.11: 'SIM_Crew' interface form

The contents of the designed interface were classified into six areas: *General Information*, *Reproduction Information*, *Crossover*, and *Mutation Information*, *Database*, and *Report groups*. *Initial population* could be generated additionally, when required.

7.5.1.1 General Information

The first area is the section of General Information in which all information regarding GA parameters had to be defined via text boxes designed especially for this purpose; these text boxes included:

- Number of generations: to decide how many generations that simulation can progress.

- Population size: represents number of chromosomes that simulation can execute for each generation.

- Chromosome size: reflects number of genes in each chromosome, each gene represents an input to a decision variable and a chromosome is considered as an input to be fed to the simulation engine.

- Total number of resources: represents all resources that were used in the manufacturing system.

- Total number of processes: reflects how many production processes were available to carry out within the manufacturing system.

7.5.1.2 Reproduction Information

The second area is the section of selection methods, which three selection methods were developed to be chosen when running a GA. The main purpose was to devise an appropriate selection rule to produce good results. The adopted selection rule was the ‘Class Interval’ selection rule.

7.5.1.3 Crossover Information

In this section, the developed Dynamic Probabilistic Crossover (DPC) operator was designed to suit this type of allocation problem. The number of gene places for the first crossover rule could be defined before progressing. The probability of a dynamic selection of gene places was useful for identification before running this type of operator.

7.5.1.4 Mutation Information

In this section, the Dynamic Probabilistic Mutation (DPM) operator was designed to suit the type of allocation problems being studied. All settings were the same as the crossover information.

7.5.1.5 Database Group

In this group, two types of databases can be reached directly to edit or check purposes.

- Excel database files: to identify order specifications and other production requirements.
- Access database files: to identify all information regarding crews, processing times, etc.

7.5.1.6 Reports Group

In this section, two types of output reports were designed to provide enough detail about the output besides showing what is happening in the optimisation engine for verification purposes.

- Output Report Type: this report can be reached by selecting *yes* or *no* options.

7.6 COMPARISON WITH OTHER SEARCHING ENGINES

7.6.1 Developing a Monte Carlo Simulation Model for the Crew Allocation Problem

Monte Carlo simulation is a type of simulation that relies on repeated random sampling and statistical analysis to compute the result (Raychaudhuri, 2008). The method works on the principle that if enough random guesses are made, eventually the right answer will be identified. The applied principle is called ‘trial and error’ which is a completely random search method.

Monte Carlo methods solve problems by executing a large number of possibility biased random actions and examining the numerical results that such actions generate. This method is used to find solutions to problems that are too complex to solve analytically. Monte-Carlo simulation has been used in many different applications (Raychaudhuri, 2008).

This study was intended to evaluate and compare two methodologies for a crew allocation system. The first methodology was based on generating a large number of equal likely sets of solutions, whilst the use of Simulated Annealing and the Genetic Algorithms were much more intelligent in terms of searching for solutions that potentially satisfy the objective of the modelling. The disadvantage of Monte-Carlo simulation being that this approach is computationally expensive to cover the entire searching space. The only advantage is that for random searching, it is very easy to use. A Monte-Carlo searching algorithm was developed to suit the allocation problem, see figure 7.12.

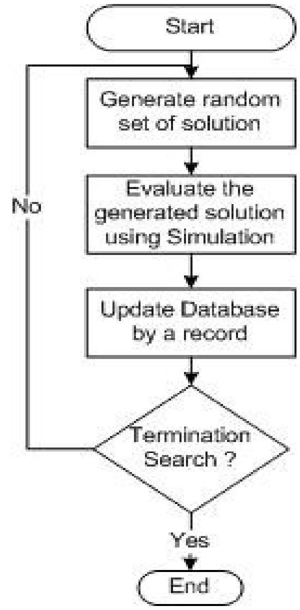


Figure 7.12: Monte Carlo sampling for Crew allocation problem

In the above sampling approach, a random set of solutions was generated using a uniform distribution. The defined parameters of that distribution being [min number of crews, max number of crews] available for each process. After forming a complete set of solutions, i.e suggesting randomly the crew of workers for a specified process, the simulation engine was run to evaluate each generated set of solutions to be stored later in a database for documentation. As a termination condition, there are no obvious convergence criteria, but the algorithm must be stopped either by allowing a specified total number of trials, or to stop when the algorithm ceases to make progress, i.e. when a stipulated number of trails has occurred, since a new best solution was last identified.

However, Monte Carlo simulation can be incorporated with Genetic Algorithms to optimise systems in a stochastic environment (Jellouli and Châtelet 2001).

7.6.2 Generating Crew Allocation Plans Using Monte Carlo Mechanism

In order to prove the performance of the proposed GA, a Monte Carlo sampling algorithm was developed as an embedded random searching engine in the developed simulation model. This algorithm was developed to provide the simulation model with a random set of solutions in terms of allocation plans.

The creation of a set of solutions starts by identifying set of inputs for both layers (day and night shift inputs). This process was started by identifying the maximum number of crew alternatives available for each process, then the random number generator (coded by VBA) generated a uniform random number (integer numbers) less than or equal to the maximum number of crew alternatives available for each process. A Monte Carlo engine was developed to create a crew allocation plan, see figure 7.13.

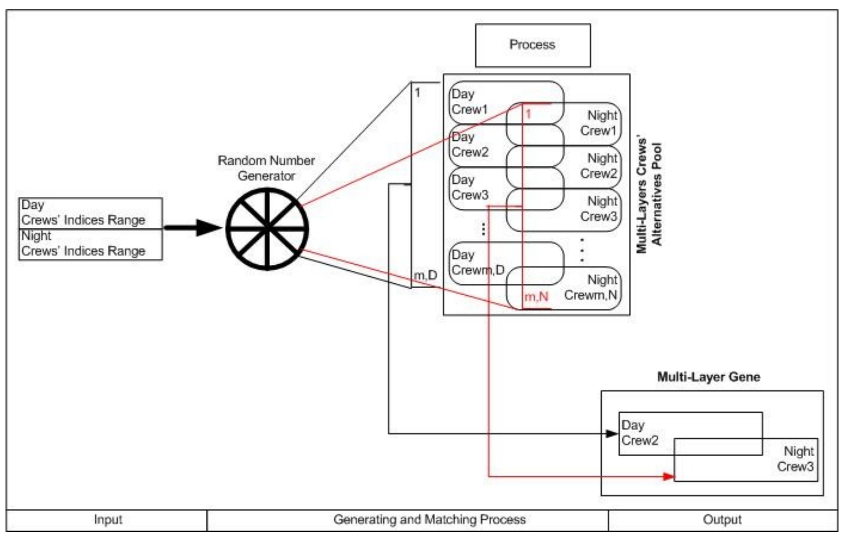


Figure 7.13: Monte Carlo engine for crew selection and allocation plans evaluation

In figure 7.13, a multi-layered gene was created by defining the maximum number of alternatives available at each layer (for each shift). Then a random number generator starts generating integer random numbers within that range (called crew index). The random number being generated to be less than or equal to the maximum number of available crews for a particular process. By matching that index with the list of crews available at the pool (stored in the Access database), the related crew is placed in the gene. This process involved two-shift working in multi-shift processes.

This process could be continued for all genes until a complete chromosome was created. Each created set of solutions being tested using the simulation engine for evaluation purposes. After testing a set of solutions, the next set of solutions was created using the developed Monte-Carlo mechanism. The creation of step by step sets of solutions was a slow process and time consuming. In addition, repetition of solution was allowed in this sort of trial-error searching. The random search for a solution eventually hits the target. The second engine to be compared with GA is developed as follow:

7.6.3 Developing Simulated Annealing Model for the Crew Allocation Problem

"The simulated annealing algorithm exploits an analogy between the way in which a metal cools and freezes into a minimum energy crystalline structure (the annealing process) and the search for a minimum in a more general system" (Busetti, 2003).

Simulated annealing creates a new solution by modifying only one solution with a local move. A special mutation operator (PDM) was developed to add the required randomness for the searching process. The optimisation loop performs a random perturbation on design variables, whose manipulation coefficient is defined by the system "temperature" (which is initially high and cools down as the process evolves). A number of cooling strategies can be used in order to lower the temperature, see Nouraniy and Andresenz (1998).

Next iteration starts with a reduction in temperature calculated by the equation (Preiss 1999):

$$_{+1}= \qquad \text{…. (7.2)}$$

where:

+1 is the next iteration temperature needed update

0< α <1

k is an index that indicates the iteration step

The worst solutions are accepted with a probability p = exp (-df/T), where df is the increase in objective function and is the system "temperature" irrespective of the objective function involved. Thus, this probability of acceptance is high at the beginning and decreases over the course of optimisation process. Due to the possibility that worse solutions can be accepted, SA's major advantage over other methods is an ability to avoid becoming trapped in local minima. The process finishes when temperature reaches some determined value or the cost function variation does not suffer relevant changes with perturbations of the variables.

The structure of the simulated annealing algorithm addressed by Busetti, (2003) was tailored to be able to solve the aforementioned crew allocation problem. See figure 7.14

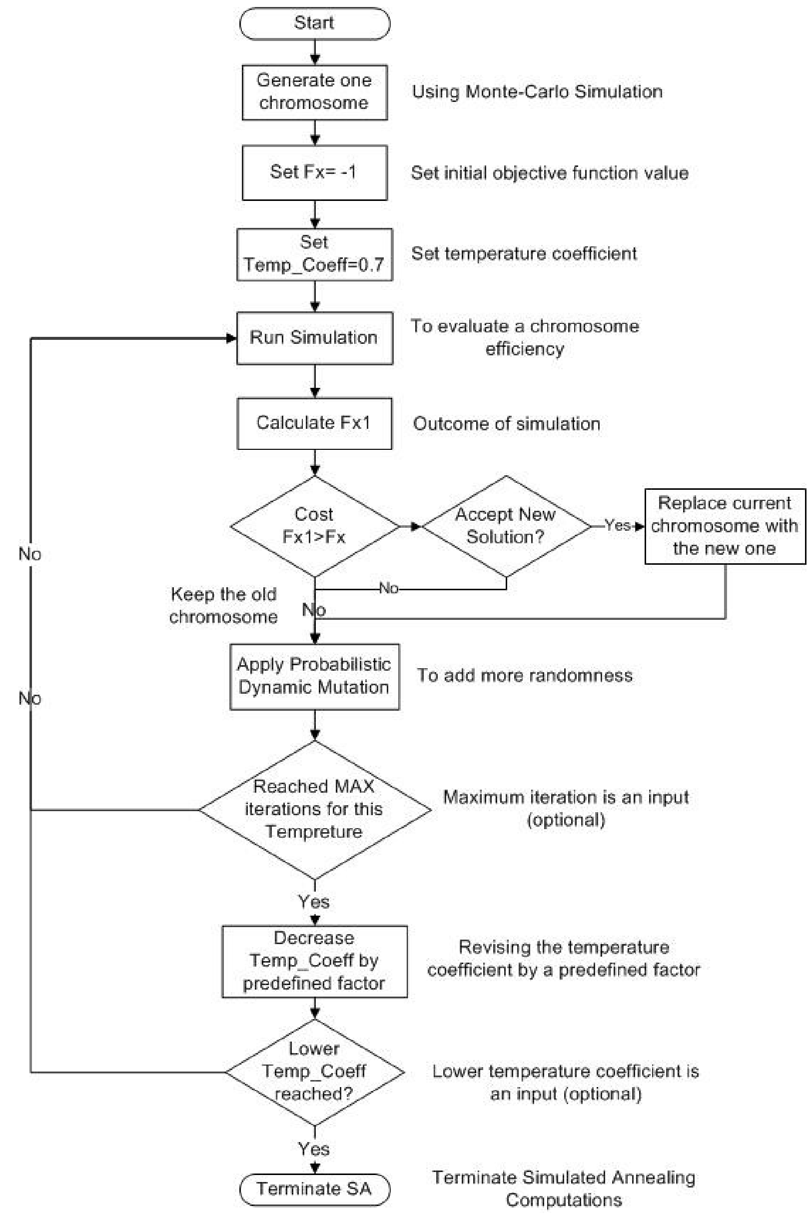


Figure 7.14: The simulated annealing algorithm (modified from Busetti, 2003)

As noted in figure 7.14, there are two major processes that take place in the Simulated Annealing algorithm. First, for each temperature, the Simulated Annealing algorithm runs through a number of cycles. The number of cycles is predetermined by the programmer. As a cycle runs, the genes are randomised. Only randomisations which produce a better-suited set of genes will be retained.

Once the specified number of training cycles was completed, the temperature could be lowered. Once the temperature is lowered, whether or not the temperature has reached the lowest temperature allowed is determined. If the temperature is not lower than the lowest temperature allowed, then the temperature is lowered and another cycle of take place. The randomisation process was customised for crew allocation system by developing the Probabilistic Dynamic Mutation (PDM) strategy.

However, if the temperature is lower than the lowest temperature allowed, the Simulated Annealing algorithm terminates. At the core of the Simulated Annealing algorithm is the randomisation of the genes. This randomisation is ultimately what causes Simulated Annealing to alter the gene values that the algorithm is seeking to minimise.

The calibration of the temperature parameter slows the process of manipulating and randomising genes, which the quality of solution depends on the selected temperature coefficient. The randomisation process takes the previous values of the genes and the current temperature as inputs. The input values were then randomised according to the temperature. A higher temperature resulting in more randomisation; a lower temperature will result in less randomisation.

7.6.4 Comparison between Genetic Algorithm, Simulated Annealing and Monte Carlo Simulation Models

The reason for using Monte-Carlo Sampling as a comparison tool was that Monte-Carlo is a random searching tool that adopts ‘trial-error’ to solve complex problems. So GA, SA and MC techniques were employed to solve this kind of combinatorial problem because of the required searching mechanism. The similarity between GA, SA, and MC is that both of them are random searching approaches which use the concept of probability in their searching. The solution space for the GA and SA can be explored using intelligent operator/operators to search for worthy solutions, while the MC approach can explore whatever random number results in a solution. This makes this kind of searching mechanism an unsuitable tool.

The advantage of the GA approach to generating a population of solutions to be tested by simulation is that it is faster than the step-by-step solution generation produced by the Monte-Carlo methodology.

7.7 CHAPTER SUMMARY

In this chapter, an optimisation module was developed in order to advance the developed simulation model with better searching capabilities. These capabilities included generating and subsequently investigating more promising allocation plans to come up with the optimal/ near optimal one.

The anatomy of the developed optimisation module was described in terms of flowcharts and algorithms involved: generating a starting basic solution in terms of initial population, accommodating a chromosome into a multi-layered structure, the 'one search' strategy which was developed to avoid chromosome repetition, the core of the optimisation engine, and the searching process for a gene in a multi-layered chromosome.

The crew allocation system interface was presented with all its contents. Three types of LOG files were developed in order to verify and validate the developed operators. In addition, developing such output files provided the mechanism of the search engine. For comparison purposes, the Monte Carlo and Simulated Annealing searching algorithms were developed.

CHAPTER 8

RESULTS ANALYSIS AND EVALUATION

8.1 INTRODUCTION

In order to prove the proposed crew allocation system, a number of intermediate results in terms of allocation plans obtained while running the GA model were analysed and evaluated. The purpose of analysing these results was to evaluate the performance of a number of allocation plans and to identify the relationships between resource utilisation and the process-waiting time and their effects on the consequent allocation cost. As each crew allocation plan results in an allocation cost, different allocation plans with various costs were selected for further analysis and interpretation.

In this section, four allocation plans with different allocation costs were selected for analysis. The reason for this selection was to identify the relationship between the performance criteria of more than one allocation plan in various allocation cost points. These plans were named as ‘Before Cost Drop’, ‘After Cost Drop’, ‘As-Is’ and ‘Best Plan’.

In this chapter, the proposed system was used as a platform to evaluate a number of allocation plans; this system indicated the efficiency of each one. The proposed system parameters were well tuned in order to guarantee better searching for promising solutions. The best allocation plan was obtained after a number of generations and a comparison between a number of allocation plans was conducted. A number of experiments were designed in order to test the sensitivity of the developed model to changing decision variables. The search engine of the proposed system was compared with other searching engines including ‘Simulated Annealing’ and ‘Monte Carlo’ sampling. The developed search engine (Genetic Algorithm) showed a better performance in terms of approaching the optimal/near optimal allocation plan.

8.2 RESULTS ANALYSIS

Four allocation plans obtained during the evolution process were selected for analysis and investigation. The incurred cost at the third generation was defined as ‘Before Cost Drop’ allocation plan. The significant cost reduction obtained at generation four is considered as the ‘After Cost Drop’ allocation plan. The one which resulted in a minimum allocation cost was considered as the ‘Best Plan’ and the current adopted one was simulated as the ‘As-Is’ allocation plan.

In order to improve the searching process for more promising allocation plans, the proposed system parameters were tuned after a number of experiments, as several sets of different probabilities were attempted without obtaining any significant effect. The best settings were as follows: a population size equal to 20, a probability of crossing over a gene was defined as 0.70, and mutating a gene was defined to be 0.90. Several sets of different probabilities were attempted without any significant effect as mentioned earlier.

The stopping condition was satisfied when there was no reduction in the resulting cost for five consecutive generations (100 solutions). Figure 8.1 demonstrates the reduction in the allocation cost using ‘SIM_Crew’ system.

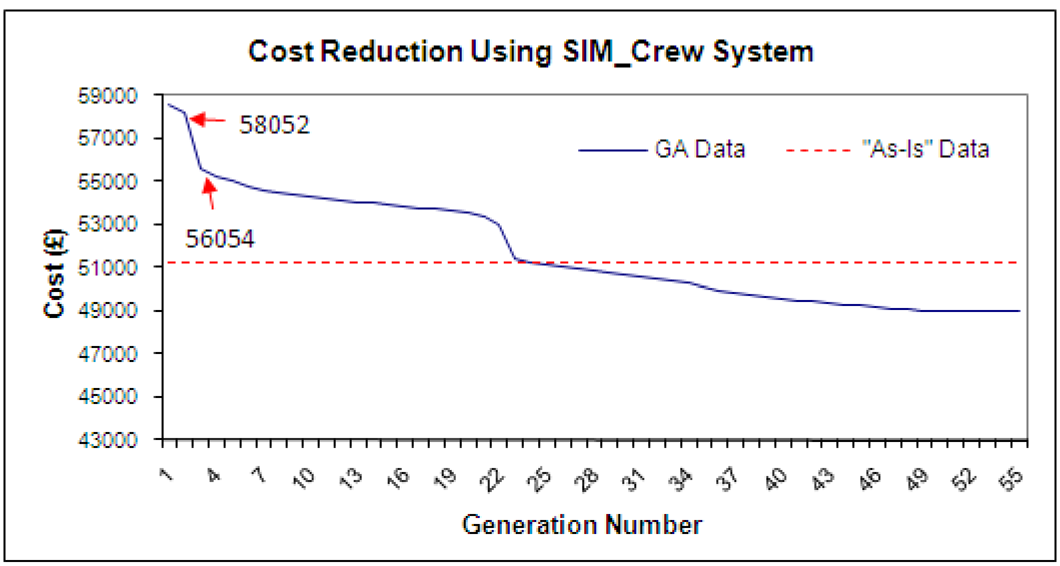


Figure 8.1: Cost reduction using ‘SIM_Crew’ system

In figure 8.1, it was noticed that a significant improvement after fifty generations was achieved in terms of reducing crew allocation cost. This significant reduction occurred early in the series of the generations (generation four) and after generation 22. The significant drop in cost occurred because the GA operators had successfully explored more promising solutions and provided the required randomness to search for good solutions.

The Probabilistic Dynamic Mutation (PDM) operator played a vital role in 'bouncing the solution away out of the trap' of the local minimum after generation 22. The high probability of mutation kept the manipulation of crews active for most processes, which eventually identifies a more promising solution after a certain amount of searching diversity. The slight difference between the process times of different crews led to a gradual reduction in allocation cost. This type of data tended to an early optimal solution after a certain number of generations.

8.2.1 The Effect of Using Different GA Operators

The comparison between GA operators was useful in identifying which operator had a substantial effect on the searching process for minimum allocation cost; see figure 8.2 for the comparison results.

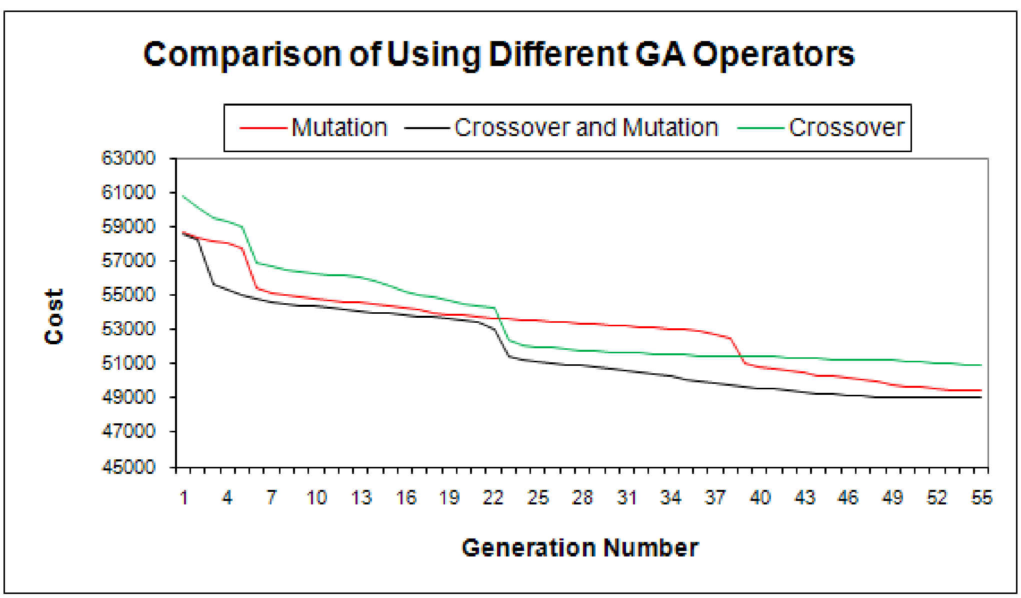


Figure 8.2: Comparison of using different GA operators

In this figure, the only use of the crossover operator shows cost approaching a non-mature solution, as the local minimum trap is more likely to appear in this case. The same number of corresponding genes (vertical crossover) was exchanged for each pair of chromosomes in which less randomness can be added to the searching process. In turn, repeated solutions were possible as the 'one search' rule was not applied for such as operator, in which good searching could be delayed. However, the application of this operator alone could not give the required randomness in the searching process and subsequently 'trapped' the solution in a local minimum case.

The mutation operator showed more randomness in terms of searching for a promising solution. The high probability of mutation continued to manipulate genes in a way that more random solutions could be explored. Different numbers of genes were mutated for each individual (chromosome). In turn, duplicated solutions were discarded as the 'one search' rule was embedded in the mutation operator for such purposes. A different number of genes were mutated for each individual, capable of speeding up the searching process.

Applying this rule added more randomness in terms of investigating various solution areas, as more random investigations were expected by running more mutations. An improved but slow approach for minimum allocation cost was achieved using this type of operator.

The application of both GA operators (crossover and mutation) generates more randomness in terms of searching for solutions that are potentially more promising. This type of application showed a significant improvement in the allocation cost and outperformed 'using each operator individually'. By applying both operators, each pair of individuals is crossed-over and then mutated individually for more randomness.

Then, the 'One Search' rule started detecting duplicate chromosomes if found and continued mutating them until uniqueness was obtained. More randomness in the searching process was obtained by adopting both operators. It was noted that the adoption of both was essential in performing a more random search in the multi-layered solution space. In addition, a mutation operator in particular was required to add more randomness in the searching process, besides replacing the duplicated chromosome with a unique one for a better search in the solution space. A minimum allocation cost was reached by exploring more alternatives in it.

8.2.2 The Relationship between Cost and Throughout Time

The relationship between the allocation cost and the throughput time (consisting of processing time and process waiting time) can be identified by comparing their curves and analysing the resulting behaviour of both. To start identifying this relationship, throughput times were calculated as shown in figure 8.3

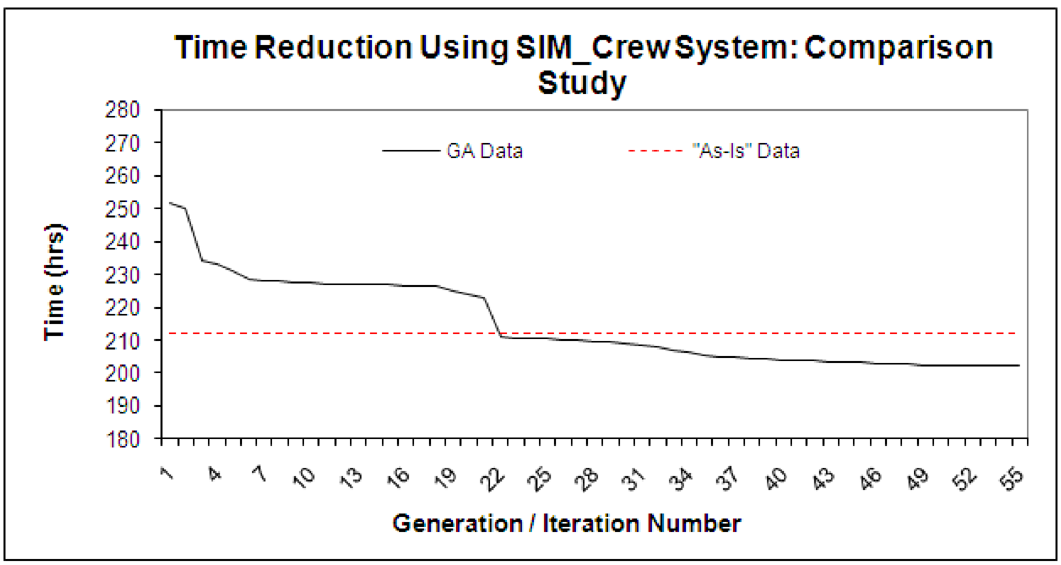


Figure 8.3: Throughput time reduction using 'SIM_Crew' system

Figure 8.3 shows similar behaviour to the resulted allocation cost curve (figure 8.1) in terms of steep falls. Relating it to the graph in figure 8.3, the smooth profile of the resulting throughput time revealed that a slight improvement in the throughput times (after thirty-five generations) was achieved, as there were slight performance differences amongst the allocation plans.

The significant drop in throughput time after generation 22 resulted in reducing the allocation cost, which in this case was related significantly with the throughput time or the production time. The aim of this comparison was to present the cause of the rapid reduction of cost was caused by the production time.

A number of influential factors affecting the allocation cost required further investigation including crew performance (process time), process-waiting time and labour utilisation. Manipulating crews, which might enable operators to be heavily involved elsewhere according to the required skills, produced a high utilisation of the assigned operators and reduced labour idle time, in turn, high process waiting time could occur. On the other hand, clash reduction amongst operators is essential to ensure a better flow of work: less overlap should be achieved in order to reduce the process-waiting time.

As a result of this analysis, it was shown that cost is highly dependent on time; direct cost is a function of time. The cost of allocating an operator can be reduced if the operator is deployed in an efficient manner. In the next section, the relationship between multi-skilled operator utilisation, process-waiting time and their effects on allocation cost will be investigated in detail through investigating and analysing four allocation plans, which were selected to prove the existence of such a relationship.

8.2.3 Effects of Optimising Labour Utilisation and Process-Waiting Time on Allocation Cost

While running the GA, possible crew allocation plans were generated and proposed by the developed searching engine in a way that a significant reduction in the allocation cost was obtained. The behaviour and relationship of cost allocation reduction in relation to resource utilisation and process-waiting time was studied and analysed by investigating four allocation plans (‘Before Cost Drop’, ‘After Cost Drop’, ‘As-Is’ and the ‘Best Plan’). The ‘cost drop’ in this context can be defined as a significant improvement achieved from any consecutive cost values.

The purpose of such an investigation was to determine whether or not allocation cost can be affected by resource utilisation and process-waiting time. This type of analysis was useful in identifying the influential factors that contribute to a significant reduction in crew allocation cost.

8.2.3.1 ‘Before Cost Drop’ and ‘After Cost Drop’ Allocation Plans

The cost incurred at the third generation and the most significant cost reduction incurring at generation four were considered as ‘Before Cost Drop’ and ‘After Cost Drop’ allocation plans.

In order to identify the relationship between skilled operator utilisation, process-waiting time and their effects on reducing allocation cost, resource utilisation and process-waiting time were adopted as performance criteria in all experiments. Skilled labourers were categorised into two main groups: multi-skilled chargehands and multi-skilled operators. Each profile was drawn up to identify the effect of utilisation and waiting time on the allocation cost.

The utilisation of skilled labourers (chargehands and operators) was considered in this study, in order to identify its relationship with allocation cost. By applying the ‘Before Cost Drop’ allocation plan, the multi-skilled chargehands (Nw02, Nw04, and w14) were heavily involved. One chargehand (w05) was less utilised in comparison with his/her utilisation obtained when adopting the ‘After Cost Drop’ allocation plan, (see figure 8.4)

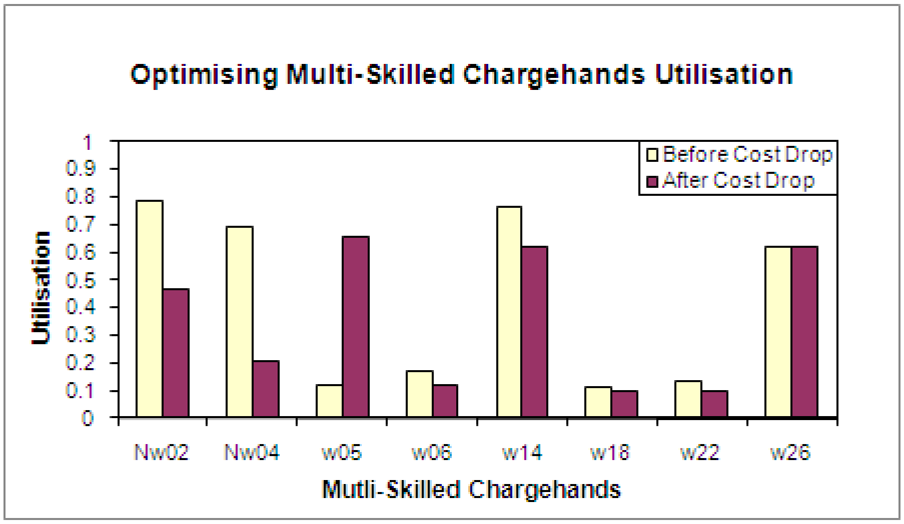


Figure 8.4: Optimising multi-skilled chargehands utilisations: 'Before Cost Drop' and 'After Cost Drop' allocation plans

In figure 8.4, Nw02, w05 represents night-shift chargehand number 02 and day shift chargehand number 05 working in section 1 respectively. In this figure, the utilisation of multi-skilled chargehands on the night shift was the major factor contributing to the overall allocation cost.

Multi-skilled night shift chargehand utilisation had an effect on the allocation cost; operators on this shift were well trained to a higher level and required less guidance and supervision. The night shift was best used for preparation and low added-value tasks to enable optimisation of the process in the morning.

The utilisation of the multi-skilled operators (14 operators) was increased to cope with the current utilisation level of the multi-skilled (both sections and shifts). This meant that there were a number of operators with the required skills that were involved heavily in certain production processes with less supervision. A number of operators were less utilised in order to achieve the required operator balance allocation. See figure 8.5 for the balanced profile of the multi-skilled operator utilisations.

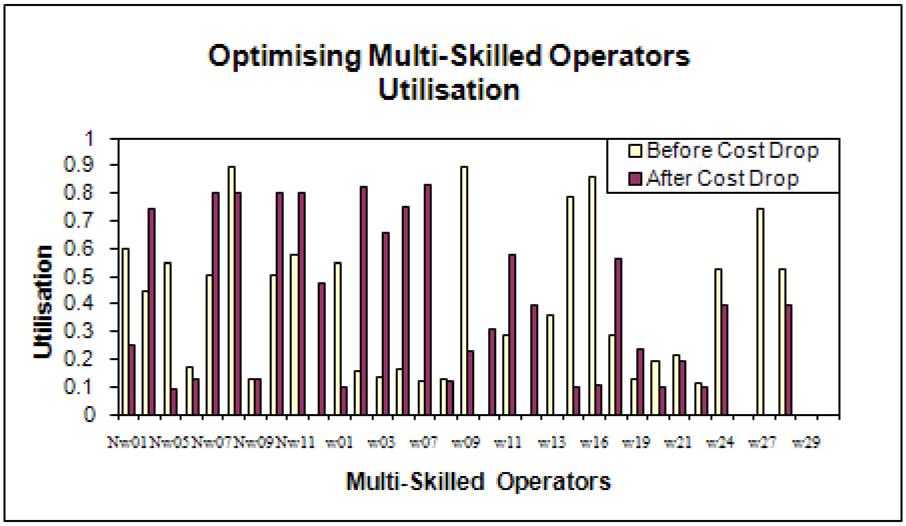


Figure 8.5: Optimising multi-skilled operator utilisations: 'Before Cost Drop' and 'After Cost Drop' allocation plans

A good allocation performance was achieved by utilising the daytime multi-skilled operators intensively for both production sections, to cope with the under-utilisation of the chargehands apparent on the day shift. A number of operators on the day shift time were used to carry out most of the production processes (9 operators). Under-utilised chargehands (Nw02, Nw04, and w05) were required to carry out work on both shifts. Four chargehands (w06, w14, w18 and w22) were under-utilised in supporting operators during the day shift in both production sections.

The crew average utilisation (arithmetical mean) was calculated using the following formula:

$$Crew\ Average\ Utilisation\ = \frac{\sum crew\ member\ utilisations}{total\ number\ of\ crew\ members}$$

In order to identify the average requirement for multi-skilled chargehand and operator utilisations to achieve a certain allocation cost, a balancing process between these was required. Figure 8.6 shows the balance and utilisation for chargehand and operators 'Before Cost Drop' and 'After Cost Drop' allocation plans.

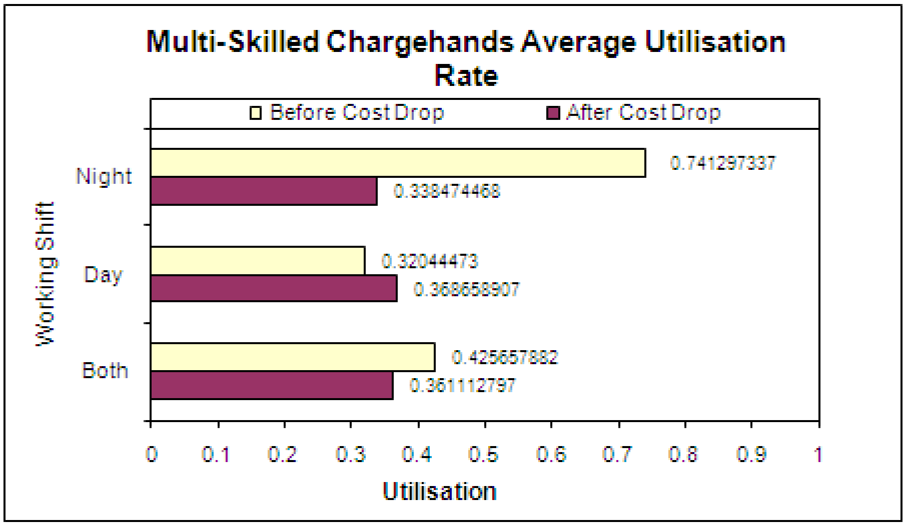


Figure 8.6: Average utilisation rates of multi-skilled chargehand and operators: 'Before Cost Drop' and 'After Cost Drop' allocation plans

It was noted that utilisation of multi-skilled chargehands during the night shift could be reduced while the average utilisation of day shift chargehands could be increased.

This type of balance leads to the achievement of the goal-seeking allocation cost (£56054). The 'operator average utilisation' was calculated in order to identify the required utilisation of such operators on each shift. Figure 8.7 shows the average utilisation for operators.

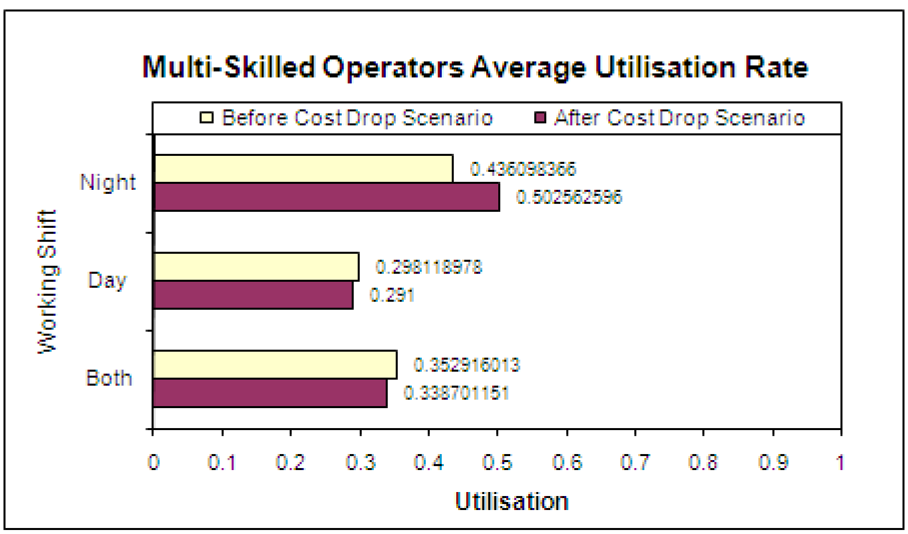


Figure 8.7: Average utilisation rates of multi-skilled operators: 'Before Cost Drop' and 'After Cost Drop' allocation plans

Figure 8.7 shows a greater need for utilising night shift multi-skilled operators to satisfy the current allocation cost (£56054) and to cope with the under-utilised chargehand situation during the same shift. This was achieved by allocating a set of crews that were able to finish the work within a time limit. The overall average operator utilisations for both shifts were nearly equal. As discussed in chapter 6, section 6.8.1, the reason for having low average utilisation of a crew working in a particular shift was because of averaging the utilisation of all crew members regardless of whether some of them were utilised or not.

Process-waiting times for both production sections were identified to check the effect of this factor on allocation cost reduction. See figure 8.8 for the average process time yielded in production section 1:

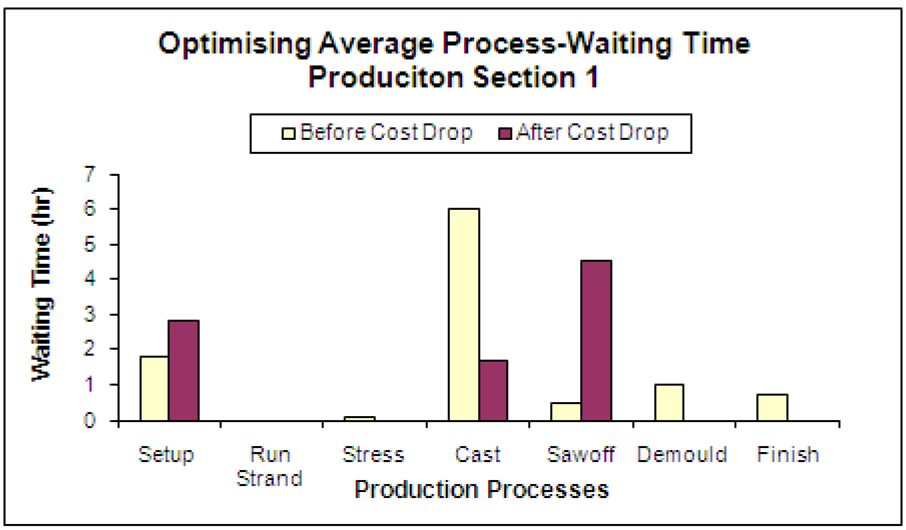


Figure 8.8: Average process waiting time of production section 1: 'Before Cost Drop' and 'After Cost Drop' allocation plans

Minimising process waiting times led to reduced allocation cost and subsequently guaranteed a better workflow. In figure 8.8, the sawoff process has a longer process-waiting time (4.5 hours) for the 'After Cost Drop' allocation plan. This waiting time was caused by the fact that members of the sawoff crew were involved in other production processes on the same/different production line. The average waiting time obtained in the second production section (one shift of working) was identified in figure 8.9:

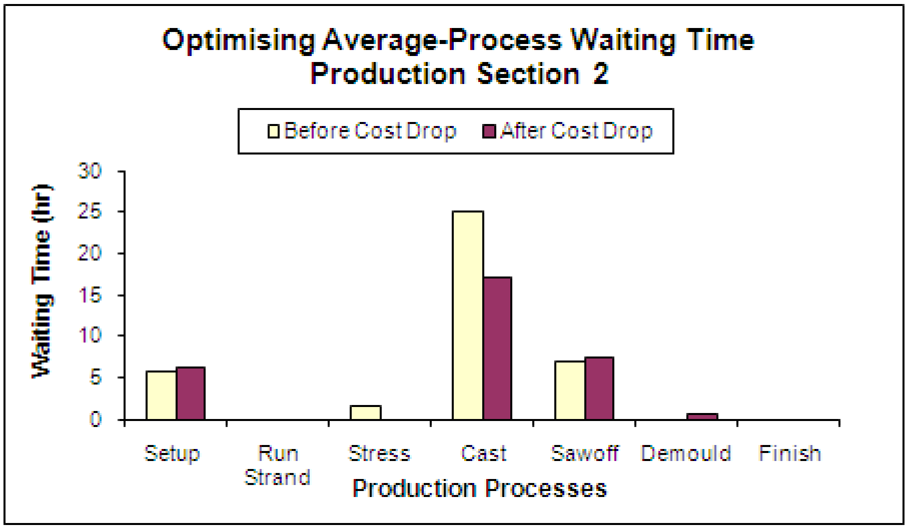


Figure 8.9: Average process waiting time of production section 2: 'Before Cost Drop' and 'After Cost Drop' allocation plans

In this figure, the casting process for both allocation plans shows a high process-waiting time of 24 hours and 16 hours respectively. These significantly longer process waiting times resulted either because the mixer was being shared to provide concrete to the first production section for both lines, or the casting crew members were fully/partially involved in other production processes for the same/different production line. However, the high allocation costs obtained by both 'Before Cost Drop' and 'After Cost Drop' allocation plans were due to the significant waiting time obtained in the sawoff and casting processes in both production sections.

The study of this type of delay was very useful in deciding how to allocate crews of workers in a way that guaranteed minimum process-waiting time and operator idle time.

The correct balance between labour utilisation and process waiting time results in the minimisation of allocation cost, which does not mean maximising labour utilisation or minimising process waiting time: rather, it means achieving the right balance between utilisation and waiting time which ensures minimum cost. The 'SIM_Crew' system has the ability to determine the optimal crew formation and the type of operators involved in that crew.

8.2.3.2. ‘As-Is’ and ‘Best Plan’ Allocation Plans

The best allocation plan resulted after running the ‘SIM_Crew’ system for 55 generations. Stability of the allocation cost was noticed after generation 50, and the next five generations do not show any cost improvement.

Both ‘As-Is’ and ‘Best Plan’ allocation plans were investigated to reveal the effect of both utilisation and process waiting time on the allocation cost. A comparative study of the ‘Best Plan’ and ‘As-Is’ allocation plans (the ‘As-Is’ allocation plan was presented in chapter 6, section 8) was necessary to reveal the value of the development of a crew allocation system that can be added to reduce allocation cost. As aforementioned, one of the ‘SIM_Crew’ system objectives was to minimise allocation cost, which was achieved by reducing throughput time, optimising resource utilisation and minimising process waiting time.

The minimum allocation cost achieved by running the GA was significantly lower than the ‘As-Is’ allocation plan, which supported the hypothesis that ‘SIM_Crew’ was capable of reducing the current allocation cost. The reduction in time by 12 hours resulted in minimising allocation cost, so around one working shift was saved by adopting the best scenario. Figure 8.10 shows the improvement in the throughput time.

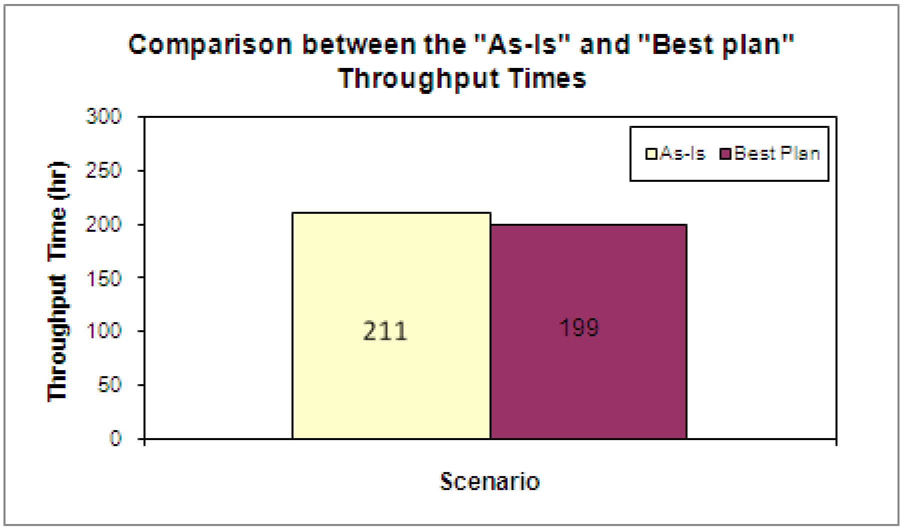


Figure 8.10: 'Best Plan' and 'As-Is' throughput times

In figure 8.10, a 5.687% reduction in the total throughput time was achieved after applying the proposed allocation system, which saved one working shift per production cycle.

In turn, cost reduction was obtained by achieving the best allocation plan. The 'Best Plan' scenario drove the allocation cost down to £49,000 producing a return of 4.295% (about £2199 per production cycle). The percentage (4.295%) was calculated using the formula:

$$\frac{\text{cost before improvemen t - cost after improvemen t}}{\text{cost before improvemen t}}$$

Optimisation of multi-skilled chargehands utilisation was balanced by the utilisation of multi-skilled operators to ensure minimum allocation cost and the shortest throughput time. See figure 8.11 for balancing utilisation of both day and night time chargehands.

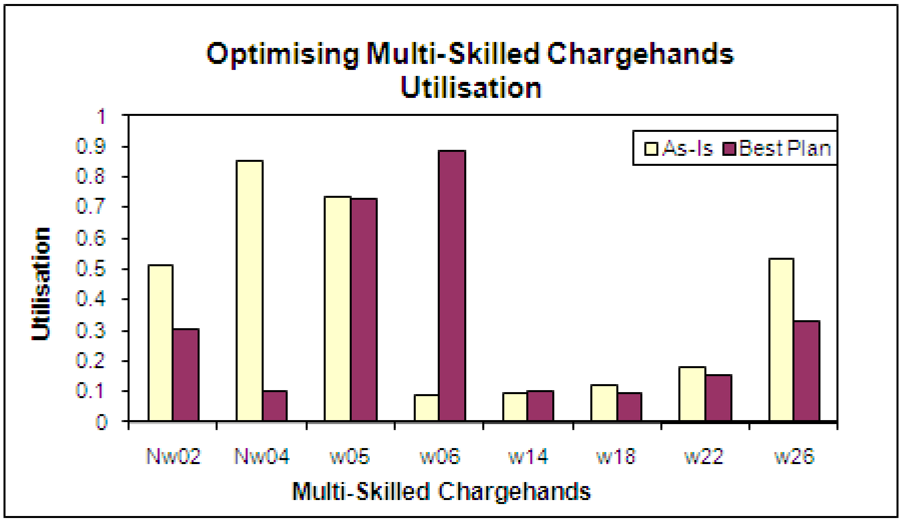


Figure 8.11: Optimising multi-skilled chargehand utilisation: 'As-Is' and 'Best Plan' allocation plans

In figure 8.11, reduced involvement of highly skilled chargehands resulted from the application of 'Best Plan' on the night shift. Chargehands w05, and w06 in production section 1 were intensively involved in providing the required assistance to all production processes during the day shift. A lower level of supervision was required to support the operators in production section 2. Operator utilisations were optimised to ensure the best balance between chargehands and operators, which eventually lead to minimal allocation costs and satisfied minimum throughput time (see figure 8.12).

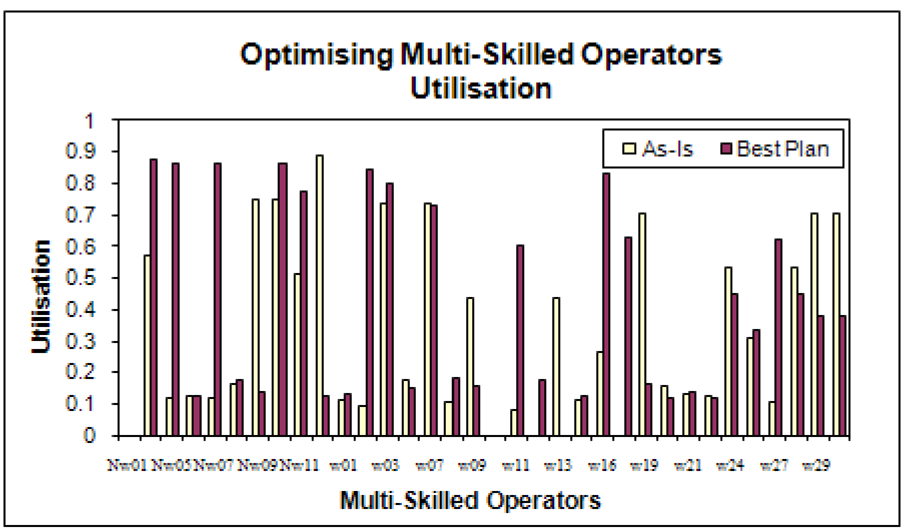


Figure 8.12: Optimising multi-skilled operator utilisations: 'As-Is' and 'Best Plan' allocation plans

In figure 8.12, a larger number of operators (13 operators) for the 'Best Plan' actual scenario were heavily utilised during the production processes based on the skill matrix of each crew.

This balance was used to maintain the required level of workforce to ensure the best workflow, eventually ensuring a minimum labour idle time. Average utilisation rates for skilled chargehands were calculated to give an overall picture of the required level of skilled workers. See figure 8.13 for optimised skilled chargehand utilisation profile.

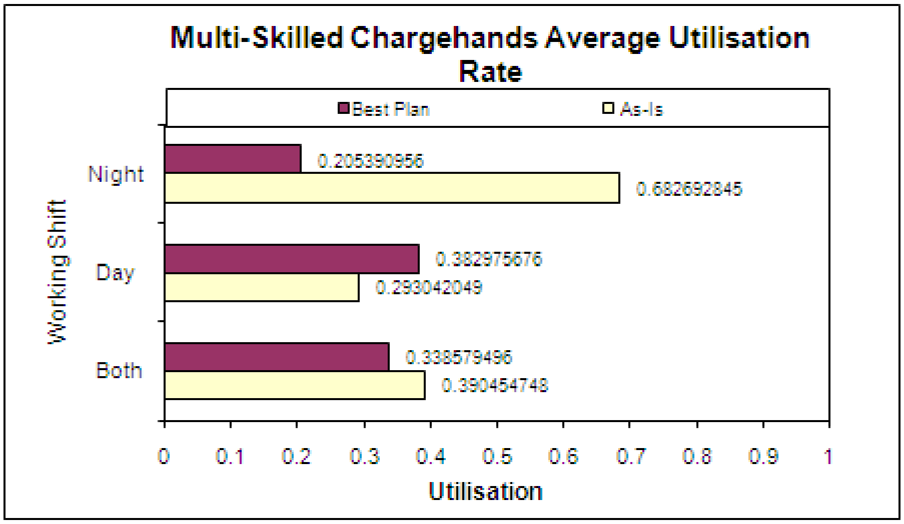


Figure 8.13: Multi-skilled chargehand average utilisation: 'As-Is' and 'Best Plan' allocation plans

In figure 8.13, less involvement of highly-skilled chargehand was required during the night shift whilst a higher level was required during the day shift. This type of balance ensured the right blend of workforce needed to carry out the work. Operator utilisation was required in order to ensure the contribution of operators to cope with the current under-utilised chargehands during the production process. See figure 8.14 for the operator utilisation profile.

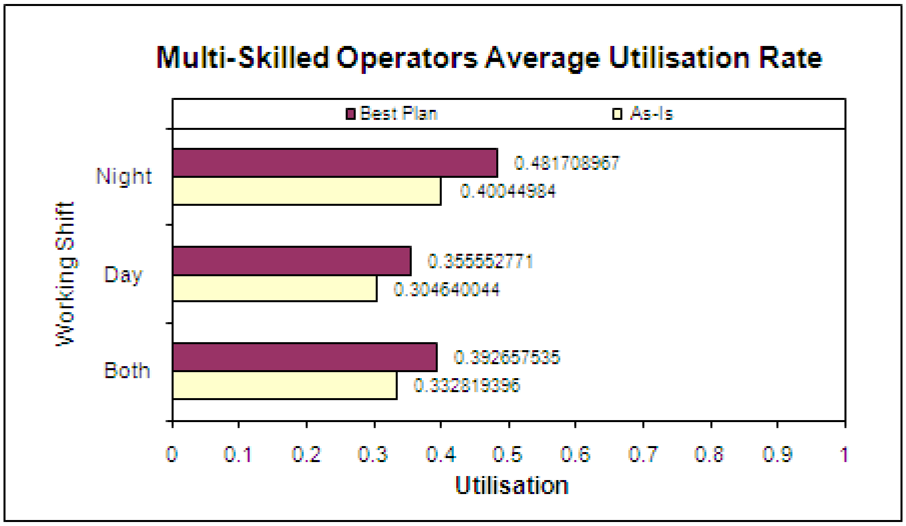


Figure 8.14: Multi-skilled operator average utilisation: 'As-Is' and 'Best Plan' allocation plans

Figure 8.14 shows that operators were utilised more during the night shift time to achieve minimum allocation time and to shorten the throughput time. During the day shift, more operators were required to satisfy production requirements. Process waiting times in each production section are identified in figures 8.15 and 8.16. By applying the 'Best Plan', the sawoff process waiting time was reduced to ensure a better workflow. Both the set-up and casting process waiting times were critical processes, as both of them utilised full/partial shared resources with other process/processes; therefore, any improvement would reduce their process waiting times.

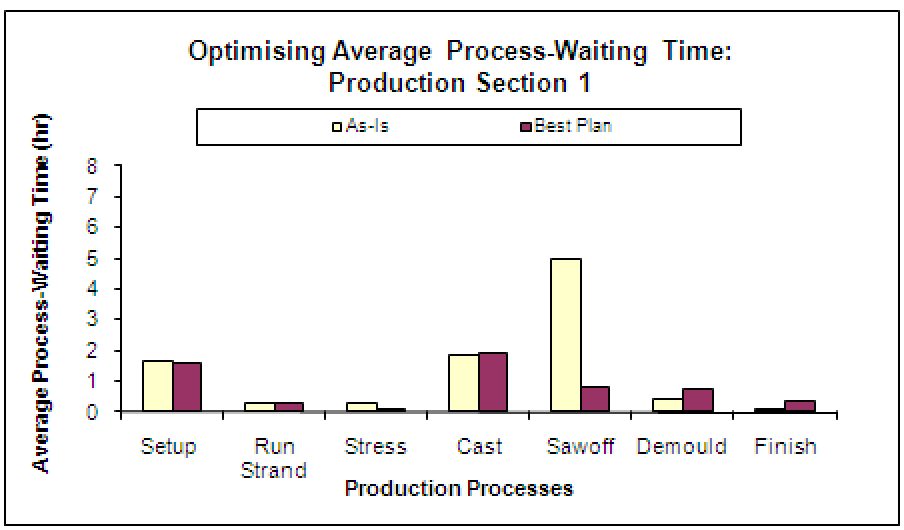


Figure 8.15: Optimising average process waiting time under 'Best Plan' and 'As-Is' allocation plans: Production Section 1

Production section 2 was involved in the optimisation process in order to guarantee the best overall workflow. See figure 8.16

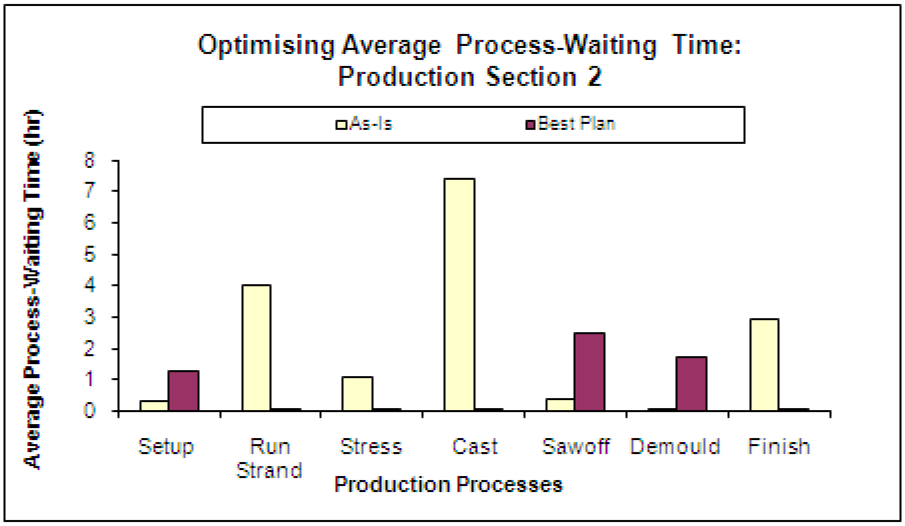


Figure 8.16: Optimising average process waiting time under 'Best Plan' and 'As-Is' allocation plans: Production Section 2

In figure 8.16, significant reductions in three production processes (run strand, cast, and finish) were observed by applying the 'Best Plan'. This reduction affected other production processes in terms of increasing process waiting times for such processes (set-up, sawoff, and demould). This balance was improved due to the reallocation process of both chargehands and operators and a lower allocation cost resulted.

8.3 A COMPARISON STUDY BETWEEN THE ALLOCATION PLANS

8.3.1 Labour Utilisation

The investigated allocation plans were '*Before Cost Drop', 'After Cost Drop*', '*As-Is'* and '*Best Plan*' allocation plans. Human resource utilisation comparisons were carried out, so both multi-skilled chargehand and operators were considered in this comparison.

The aim of this comparison was to identify which utilisation profile should be adopted as a best labour utilisation profile that can lead to a minimum allocation cost.

Human labour utilisation was calculated by identifying the average utilisation value in each skill category (two categories were considered in the study: chargehand and operator). An average skilled utilisation was calculated for each allocation plan. See figure 8.17 for the calculated average utilisation obtained by applying each of the allocation plans.

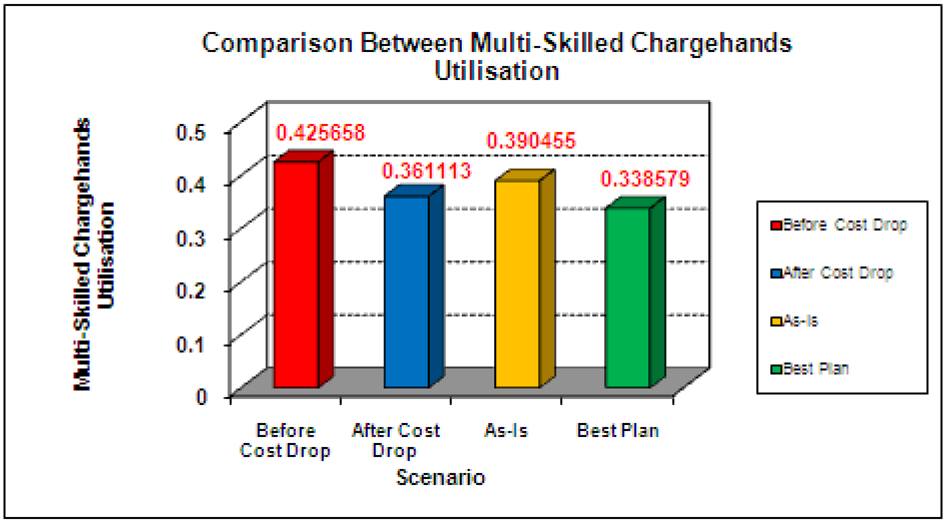


Figure 8.17: Comparison between multi-skilled chargehand utilisations under different allocation plans

In the 'Before Cost Drop' allocation plan (figure 8.17), four multi-skilled chargehands in both sections were intensively involved in supporting operators to carry out their tasks. A reduced level of support by only three multi-skilled chargehands was provided in the 'After Cost Drop' scenario to guide the multi-skilled operators.

In the 'As-Is' allocation plan, only two multi-skilled chargehands were involved in providing the required assistance to multi-skilled operators. Less support was necessary from three multi-skilled chargehands in the 'Best Plan' allocation plan. In order to obtain a full picture of the utilisaiton profile of both skill categories (chargehands and operators), a multi-skilled operator utilisation profile was calculated and is depicted in figure 8.18.

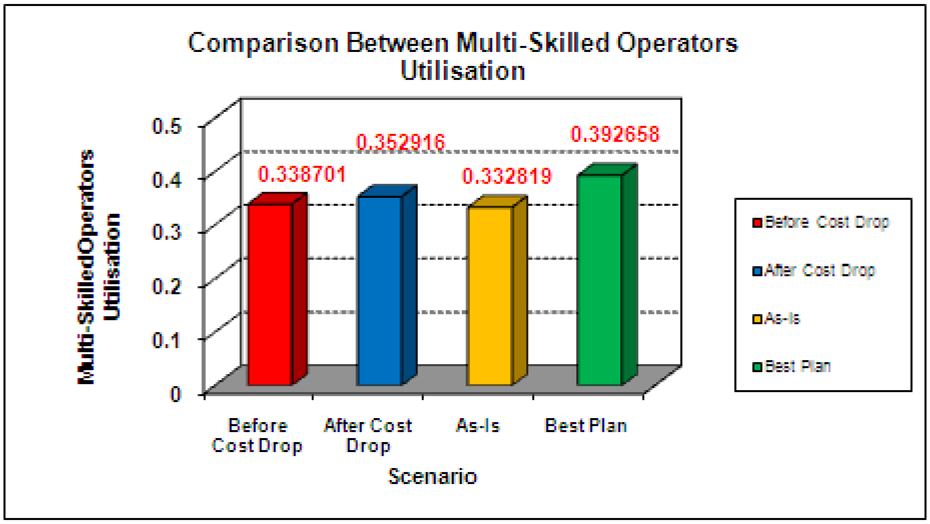


Figure 8.18: Comparison between multi-skilled operator utilisations under different allocation plans

The 'Best Plan' featured a reduction in the requirement for multi-skilled chargehands supporting 13 multi-skilled operators. This type of allocation led to an increased distribution of tasks amongst a larger number of operators, rather than focusing on the multi-skilled chargehands.

Multi-skilled operators were utilised more in the 'Best Plan'. This high utilisation rate resulted in a minimised average process-waiting time in both production sections and it was useful in producing a better workflow. Insufficient recruitment of operators was a substantial reason for high process-waiting time achieved in 'Before Cost Drop' and 'After Cost Drop' scenarios. The allocation of a reduced number of operators led to a high process-waiting time in both production sections as in the 'As-Is' scenario.

The balance between multi-skilled chargehand and operator utilisation profiles was important in achieving the targeted level of utilisation. The highest level of utilisation in a skilled category was meaningless without considering the utilisation level of the rest of the skill categories. The optimisation of the utilisation profile was a key factor in enabling the reduction of the process-waiting time by selecting the optimal/near optimal collection of operators.

8.3.2 Process-Waiting Time

In this section, a comparison is made in terms of identifying the average process-waiting times yielded in each production section. The average process-waiting times were calculated by computing the average value of process-waiting time for each production process of each allocation plan. Figure 8.19 shows the comparison of average process times obtained in production section 1.

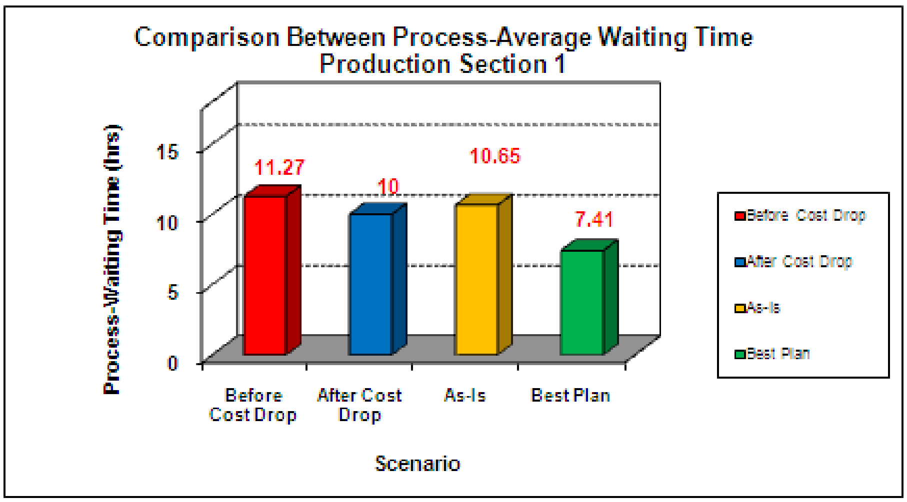


Figure 8.19: Comparison between process-average waiting time under different allocation plans: Production section 1

In this figure, it was noticed that the 'Best Plan' allocation plan achieved minimum average process-waiting time. The reduction of process-waiting times in this section was not significant, as it was based on two shifts and involved critical processes which have to be completed before, or may be delivered to the next working shift for completion.

Production section 2 was working on a one-shift basis, and the incomplete work had to wait until the next day. The section had a longer time associated with the desired type of products, and by adopting one working shift in that section, a significant process waiting time was yielded due to the restriction of time and the shared skilled operators. See figure 8.20 for comparison of average process-waiting time yielded in that section.

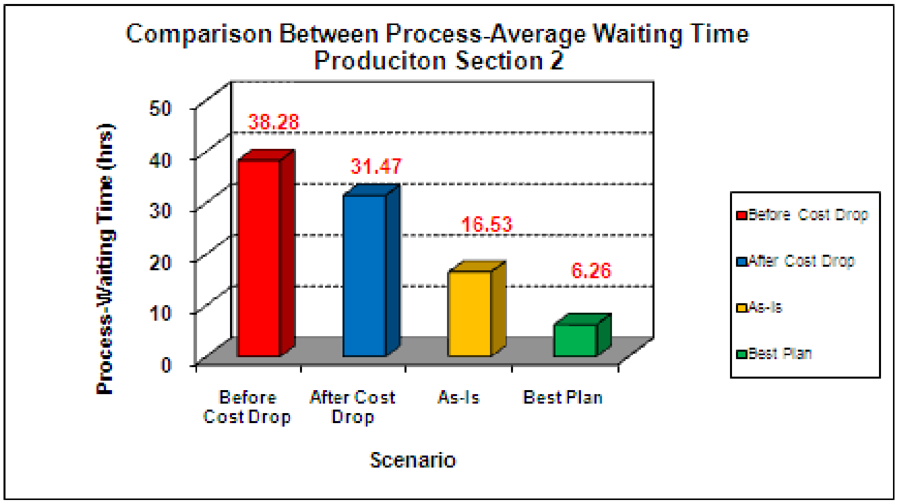


Figure 8.20: Comparison between process-average waiting time under different allocation plan: Production section 2

Allocating fewer numbers of multi-skilled operators in production section 2 as shown in the '*After Cost Drop*' allocation plan led to significant process-waiting time, and a number of operators such as w25, w27, w29, and w30 were not utilised at all. This type of allocation led in turn to a significant reduction of the process-waiting time obtained in production section 2 from 31.47 hours to 6.26 hours (see figure 8.20).

The 'As-Is' scenario had showed an average process-waiting time below the other scenarios except the 'Best Plan'. The 'As-Is' scenario currently run by the company resulted in additional labour allocation cost due to a high average process-waiting time (16 hours and 53 minutes) in this production section causing a significant cost problem. This caused additional process-waiting time leading to process-waiting and labour idle times. The best allocation plan resulted in a significant reduction in the average process-waiting time, which assisted in the reduction of labour allocation cost.

The process-waiting time had a significant impact on the total labour allocation cost. Detailed investigation was necessary to identify which process was critical in terms of having a high waiting cost before completion. See figures 8.21 and 8.22 for the detailed process-waiting time analysis for each production process at each production section under different allocation plans.

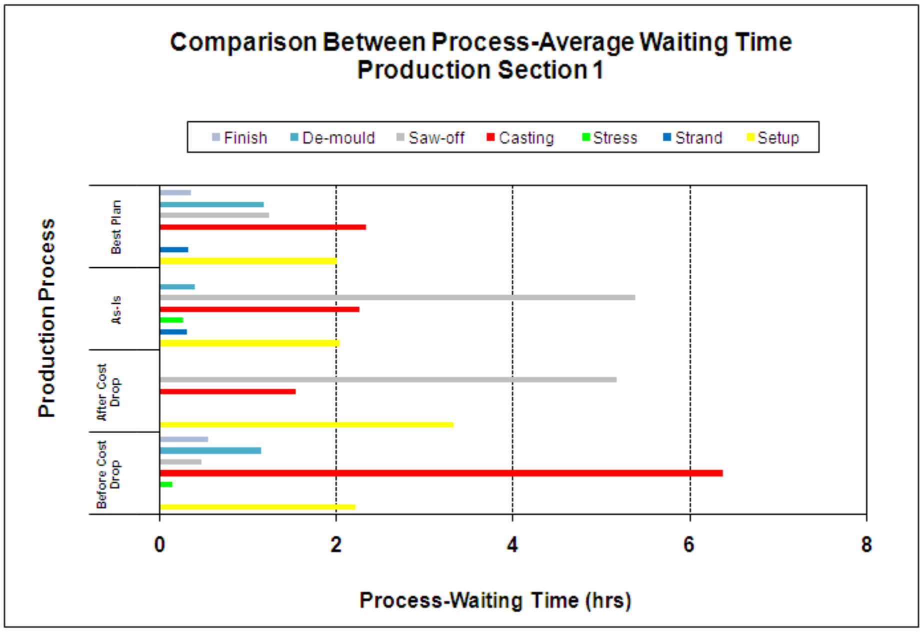


Figure 8.21: Comparison between process-average waiting time under different allocation plans: Production section 1

It can be seen that both 'casting' and 'saw-off' processes had the highest waiting time. The reasons behind this were either the use of a shared mixer or sharing full/partial sharing skilled operators in more than one process. The high waiting time obtained in the sawoff process resulted because both cured concrete moulds were required to be completed in line with a shared sawoff machine to cut the cast body before de-moulding it.

For production section 2, higher casting process-waiting times resulted from a priority of providing mixed concrete to production section 1, besides sharing skilled operators in more than one process. In addition, adopting one shift was sufficient to cause a significant process-waiting time, especially when shared skilled operators were required to accomplish jobs in the same production processes (see figure 8.22).

According by the 'As-Is' scenario adopted by the company, and after investigating the shift pattern with the production manager, it was noted that production section 2 line 2 was sometimes waiting for the casting process to be conducted on its mould, as one shift was not enough to cast both production lines. See figure 8.22 for the average process-waiting time yielded by running different allocation plans in production section 2.

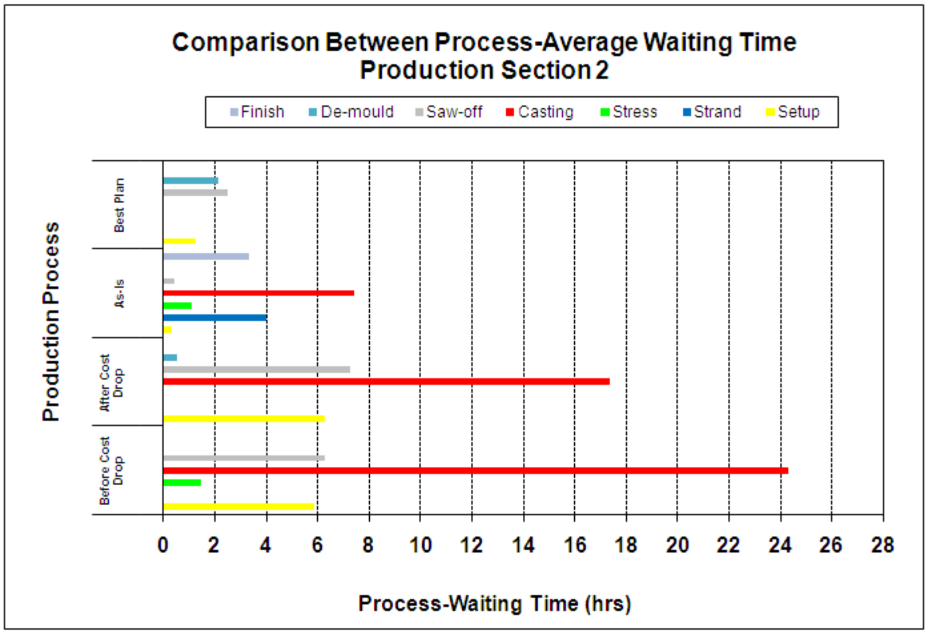


Figure 8.22: Comparison between process-average waiting time under different allocation plans: Production section 2

Production section 2 had its own crew of workers and adopted one shift. The set-up process was longer than for production section 1, which meant that the average process-waiting time was longer than section 1. However, the best allocation plan guaranteed a minimum average process-waiting time as the casting process was eliminated, because of achieving a 'series' processing work pattern which allowed waiting times to be minimised.

In production section 2, one shift was enough to cast only one mould, as the second mould has to wait until the next day, since the time available is only enough to cast three production lines (moulds) and that was the evident production capacity. In production section 2, the best plan scenario shows that there is no casting waiting time because of the synchronisation achieved in the work progress. Both lines of production section 1 were faster than line 1 in production section 2, which made the casting process in both production sections as a parallel process with no delay. The fourth production line was scheduled to wait until the second day, so there was no waiting time for this line.

8.4 SENSITIVITY ANALYSIS

The objective of this section is to conduct sensitivity analysis and identify control factors that influence the model outputs and performance. A number of experiments were conducted, the process-waiting times in a number of allocation plans were occurred due to sharing resources are considered. A number of processes that could not be executed on time because of multi-skilled operator sharing were considered as delayed processes.

A number of factors that influence the delayed processes were considered while designing the following experiments:

- Adding additional operators (3 chargehands and 7 operators in total)
- Decrease crew alternatives

Details of the experimental work are presented below:

8.4.1 Experiment 1: Adding of Additional Operators to Selected Processes ('*Sawoff*', '*Run-strand*', '*Casting*', and '*Finishing*')

This experiment was designed after investigating the process-waiting times obtained by considering the 'As-Is' allocation plan. It was noted that the process waiting time of the 'sawoff' process in production section 1, 'run-strand', 'casting', and 'finishing' in production section 2 were significantly high (see figures 6.17 and 6.18).

In order to test the sensitivity of the developed model, additional multi-skilled operators (those working in other production sections) were deployed to each of the 'sawoff' processes in both shifts in production section 1 and additional multi-skilled operators were added to each of the 'run strand', 'cast', and 'finish' processes of section 2. The purpose of this experiment was to identify sensitivity of adding additional operators to the processes mentioned on the model outputs. The result of this experiment is shown in figure 8.23

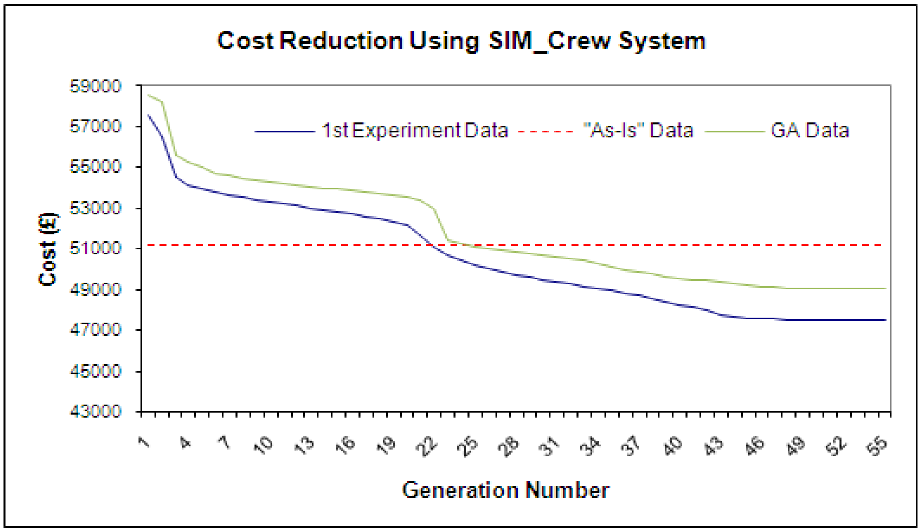


Figure 8.23: The effect of adding additional operators to the delayed production ('sawoff', 'run-strand', 'casting', and 'finishing') processes

Figure 8.23 shows that a lower allocation cost was obtained by adding additional number of operators for each of the delayed processes. The adoption of additional operators reduced the allocation cost to £47,350 producing a return of 3.367% (approximately £1650). After assigning additional skilled operators, the resource allocation cost was increased by 0.533%, so the resource allocation cost for the 'Best Plan' scenario was £46727 and increased to £46976 after adding additional operators to a number of production processes.

Adopting additional multi-skilled operators brought from other similar production sections can minimise operator overlap. See figure 8.24 for the process waiting time obtained in production section 1.

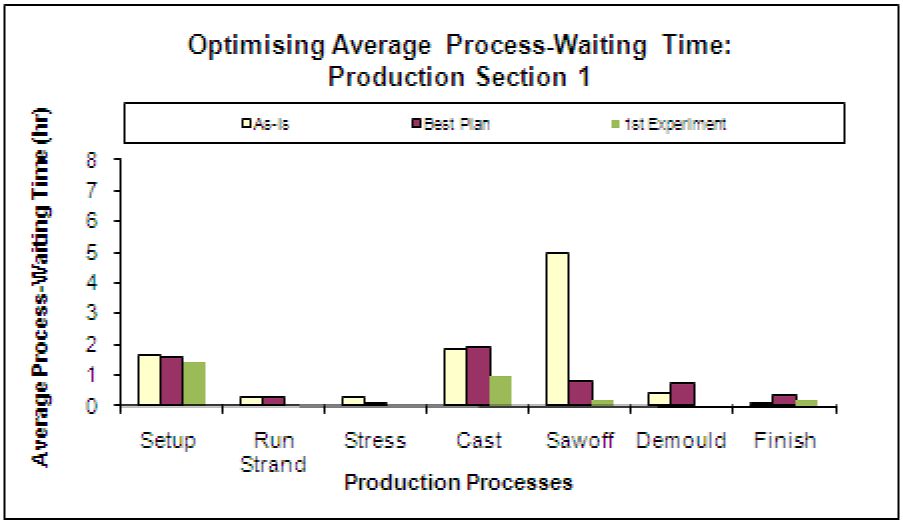


Figure 8.24: The process waiting time obtained after adding additional operators to the delayed 'sawoff' process in production section 1

In figure 8.24, the adoption of additional operators resulted in less resource overlap. The work flow is improved from less process-waiting time in each of the shared resource processes (cast and sawoff). The involvement of additional operators to carry out activities saved more than 6 hours of waiting time, which subsequently led to reducing the resource sharing problem. Adding additional operators to the sawoff process on each working shift reduced waiting time and improved the workflows in the subsequent demould and finish processes. The adoption of additional operators to the delayed processes in production section 2 is shown in figure 8.25:

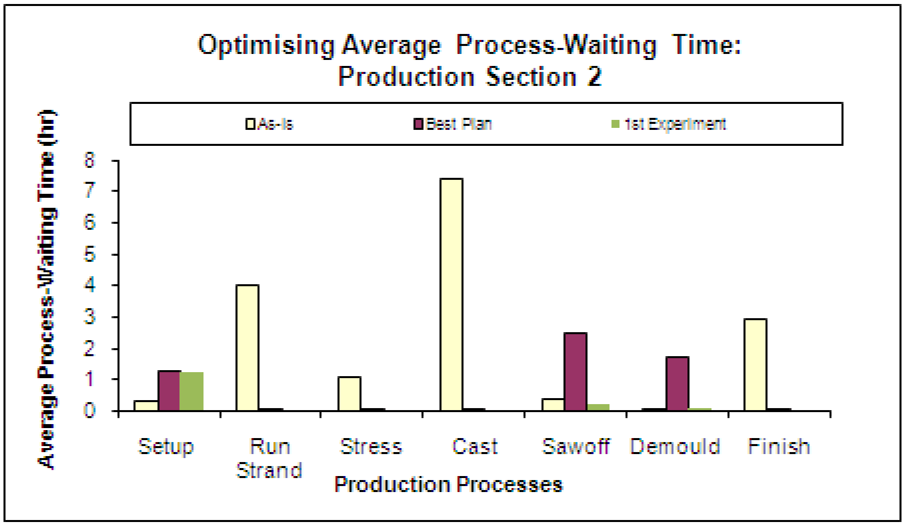


Figure 8.25: The process waiting time obtained after adding additional operators to the delayed 'run-strand', 'casting', and 'finishing' process in production section 2

In figure 8.25, the workflows in the casting, sawoff and demoulding processes were improved as a consequence of adopting additional operators to the casting process. However, the reduction of process-waiting times significantly contributed to minimising the idle cost of operators by saving more than 9 hours in both production sections. Adding additional operators to the 'delay processes' decreased the resource idle cost by 83.55% (the cost of idle resources for the 'Best Plan' was £2273 and decreased to £374 after adding additional skilled operators).

8.4.2 Experiment 2: Adding of Additional Operators to Selected Processes ('*Casting*', '*Setup*', and '*Sawoff*')

In the 'Cost Drop' allocation plan, it was noted that process times of the 'casting' process in production section 1 and 'setup', 'casting', and the 'sawoff' processes in production section 2 were significantly high as shown in figures 8.8 and 8.9.

In this experiment, additional multi-skilled operators were added to the 'casting processes for both shifts of production section 1. Additional operators were added to each of the 'setup', 'cast' and 'sawoff' processes in production section 2. The adoption of additional multi-skilled operators in the processes mentioned contributed to reducing the total allocation cost as shown in figure 8.26:

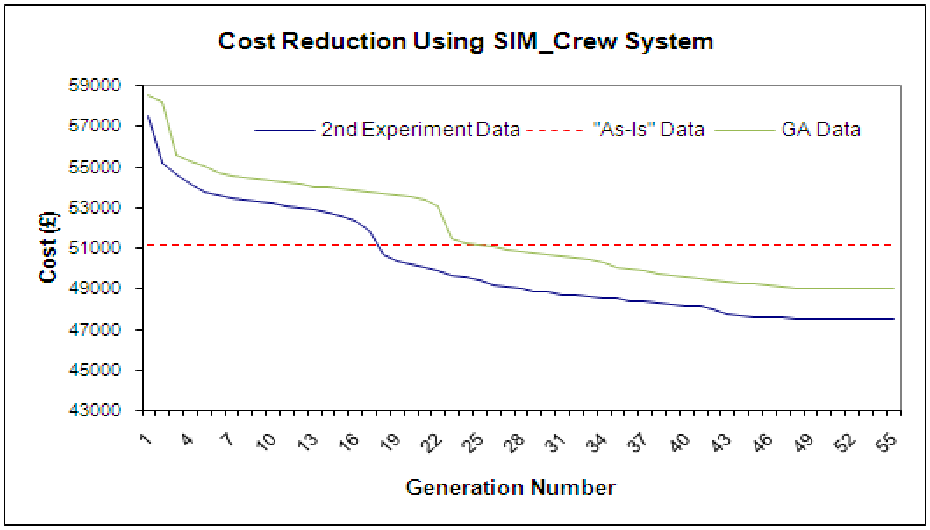


Figure 8.26: The effect of adding additional operators to the delayed processes ('casting', 'setup', and 'sawoff')

Figure 8.26 shows that adding additional multi-skilled operators to a number of production processes in both sections resulted in a slightly better results in terms of cost reduction when compared with the cost obtained from experiment 1. The reduction in cost was significantly greater than that obtained from the first experiment. Stabilisation of cost in both experiments was achieved after generation 51. However, minimum allocation cost achieved in this experiment was slightly better than in the first experiment.

The reduction of process-waiting times obtained in a number of production processes in both production sections are shown in figures 8.27 and 8.28.

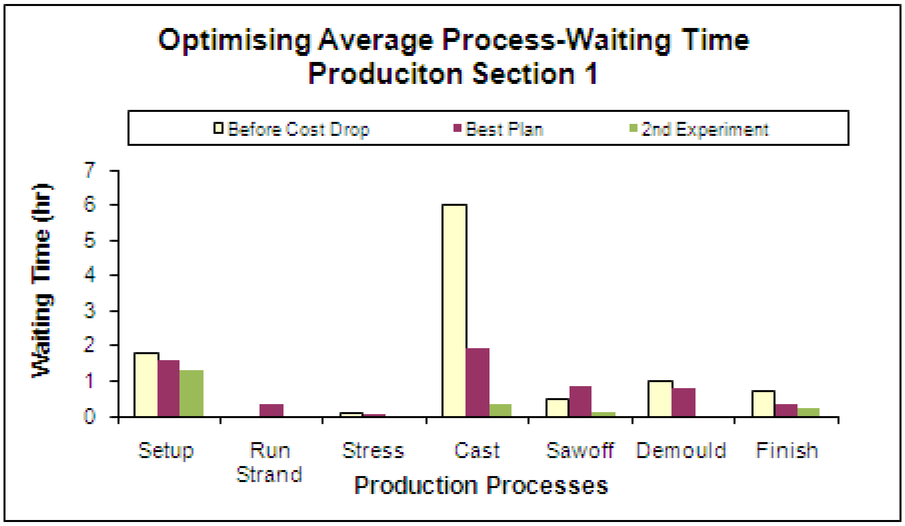


Figure 8.27: The process waiting time obtained after adding additional crews to the delayed 'casting' process in production section 1

In figure 8.27, the process-waiting times of both sawoff and casting processes were reduced when additional crews were provided to avoid resource overlap. A significant reduction in the waiting times was achieved in the second production section as shown in figure 8.28.

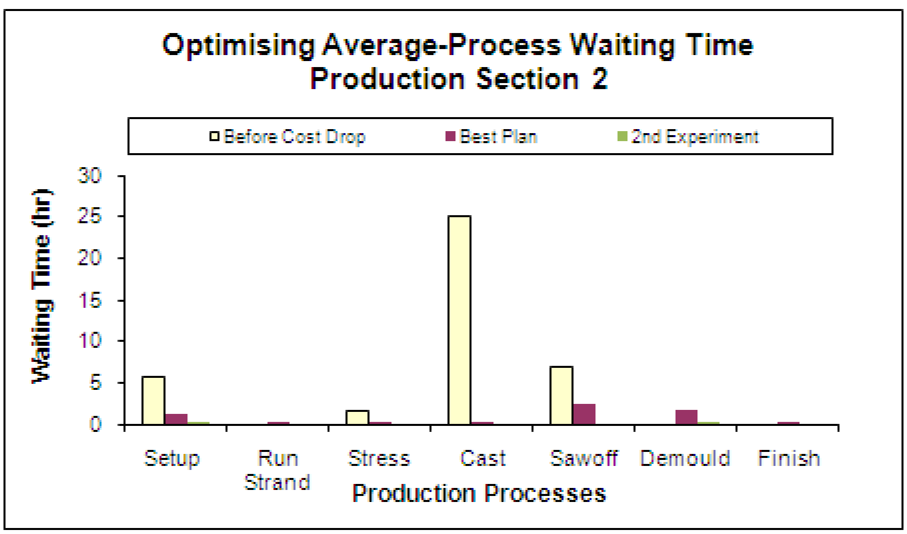


Figure 8.28: The process waiting time obtained after adding additional operators to the delayed ('casting', setup', and 'sawoff') processes in production section 2

In the second production section, the adoption of additional multi-skilled operators in ‘setup’, ‘cast’, and ‘sawoff’ processes was contributed significantly to guaranteeing a better workflow.

8.4.3 Experiment 3: Decrease Crew Alternatives for Selected Processes (‘*Casting*’, ‘*Setup*’, and ‘*Sawoff*’)

This experiment was similar to experiment 1 in terms of the selected delay processes; the only difference being that the crew alternative with the greatest processing time available for each of the delayed process was discarded. The purpose of reducing the number of crew alternatives was to investigate the workflow effects of involving fewer crew alternatives in carrying out tasks in number of the production processes (see figure 8.29).

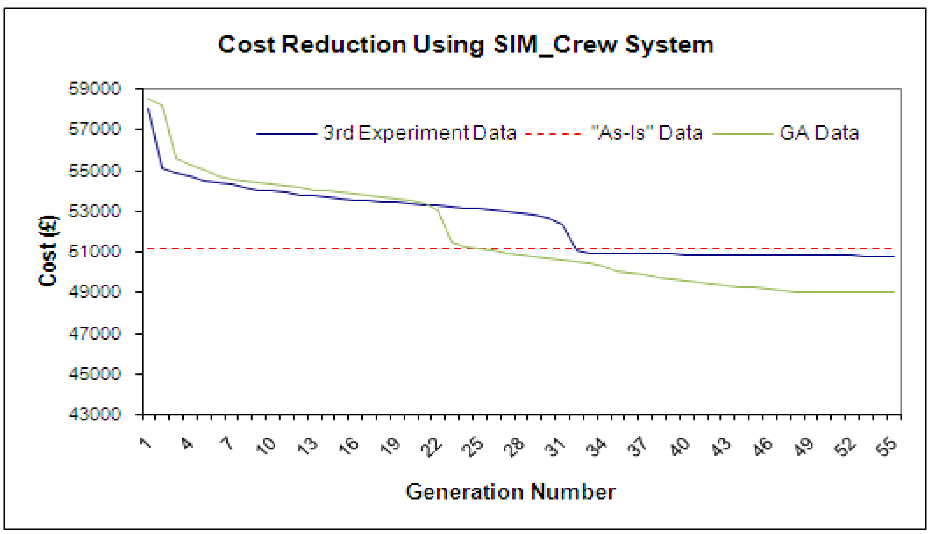


Figure 8.29: The effect of reducing crew alternatives of the delayed processes (sawoff, run-strand’, ‘casting’, and ‘finishing’)

Figure 8.29 shows that a significant increase occurs as a result of operator sharing. Taking the crew alternatives associated with the highest process time for the delayed process resulted in a significant sharing problem, where fewer numbers of multi-skilled operators were available to carry out a wide range of tasks in a number of production processes.

As a consequence, the allocation cost increased by 3.67% (about £1800) due to reducing crew alternatives for a number of processes. This resulted in a reduction of the resource allocation cost by 3.45% (the ‘Best Plan’ resource allocation cost of £46727 fell to £45117 after discarding a number of crews). The process waiting times in section 1 were increased as shown in figure 8.30.

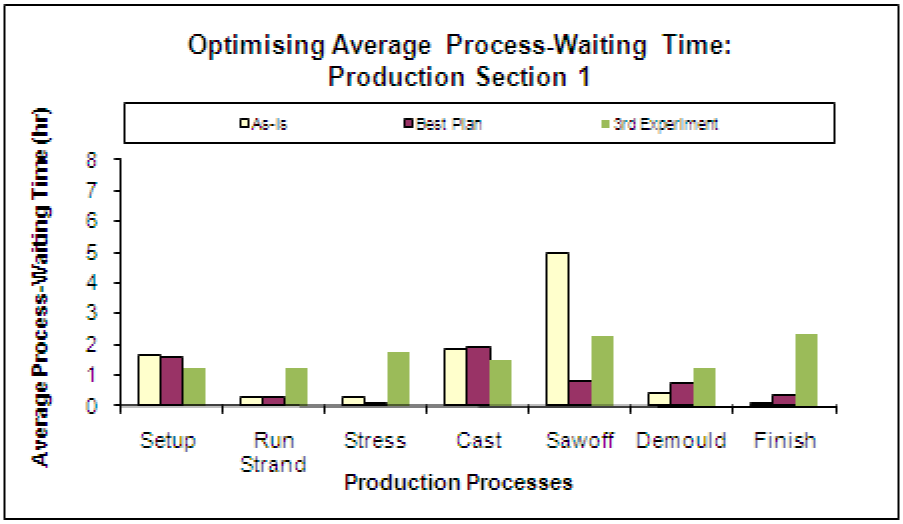


Figure 8.30: The obtained process waiting time after reducing one crew for each of the delayed ‘sawoff’ process in production section 1

In figure 8.30, an increase in the process times of sawoff, demould and finish processes was noticed as a result of reducing crew members of the sawoff process in production section 1.

However, the reduction of crew alternatives in the processes affected the flow of work of other production processes including setup, run strand and stress. The production process in section 2 was affected due to lower crew members associated with a number of processes as shown in figure 8.31.

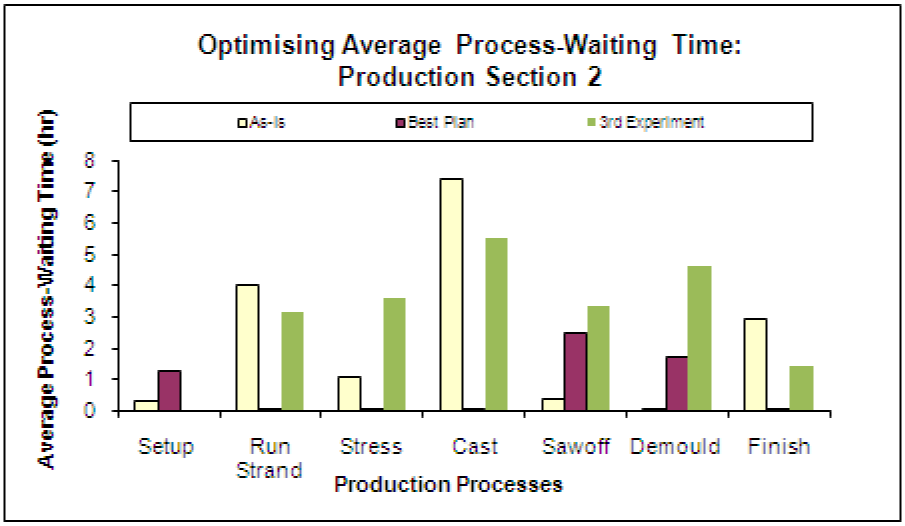


Figure 8.31: The obtained process waiting time after reducing one crew for each of the delayed processes ('run-strand', 'casting', and 'finishing') in production section 2

In figure 8.31, reducing crew members in 'run strand', 'casting', and 'finish' processes resulted in disturbing the work flow in a number of processes in production section 2, as the number of operators was limited. The idle resource cost for the 'Best Plan' increased by 1.5 times (the idle resource cost resulting from discarding a number of crews was £5683).

8.4.4. Experiment 4: Decrease Crew Alternatives for Selected Processes ('Casting', 'Setup', and 'Sawoff')

In this experiment, the highest process time crew alternative available for each delayed production process ('setup', 'cast', and 'sawoff') was discarded. The crew alternative reductions resulted in increasing the allocation plan as shown in figure 8.32.

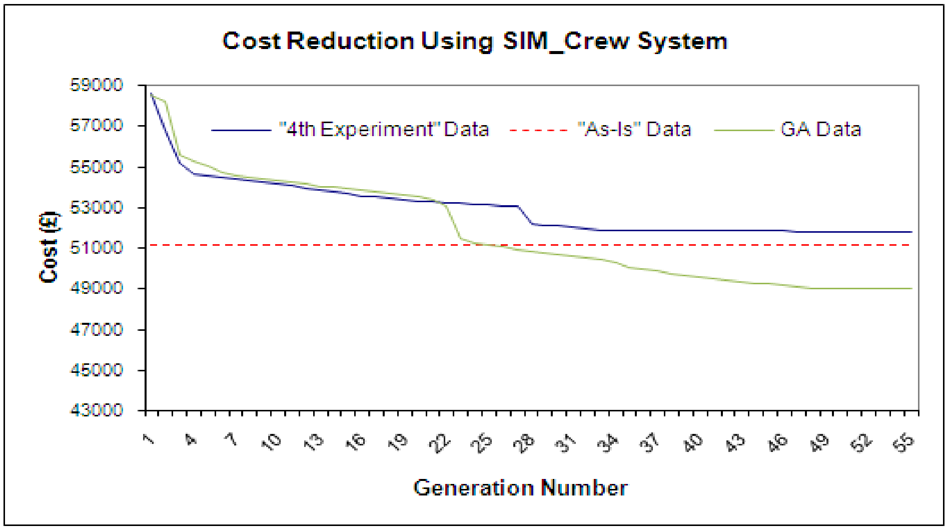


Figure 8.32: The effect of reducing one crew for each of the delayed ('casting', setup', and 'sawoff') processes

Figure 8.32 shows that a significant increase in allocation cost is achieved, as a smaller number of crews was available to carry out various tasks in a number of production processes. Allocation cost increased by 6.08% (about £2980) due to the limited availability of operators which caused a significant resource sharing problem. The process-waiting times were significantly increased in both production sections 1 and 2 in response to reducing crew alternatives as shown in figures 8.33 and 8.34:

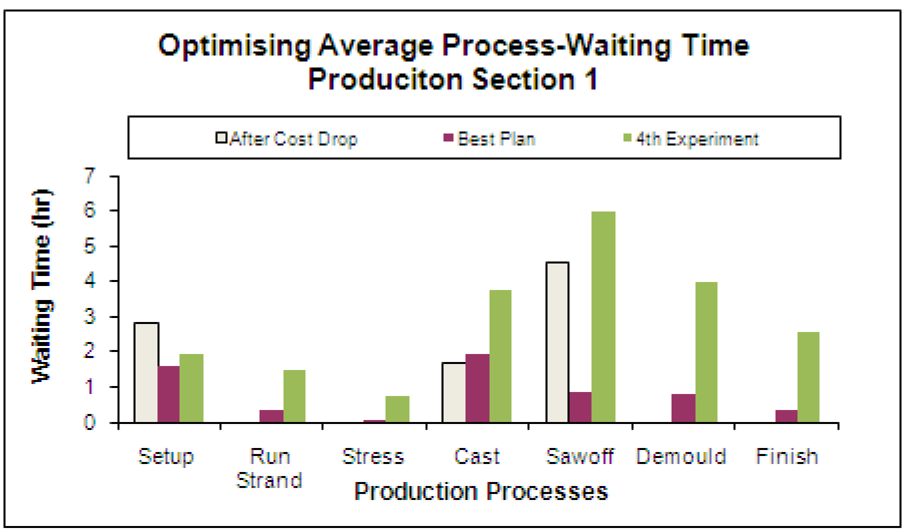


Figure 8.33: The obtained process waiting time after reducing one crew for each of the delayed 'casting' process in production section 1

The effect of taking out a crew from the 'sawoff' crew alternatives list affected the workflow. The process waiting times were increased in production section 2 as a result of reducing crew alternatives from a number of its processes (see figure 8.34).

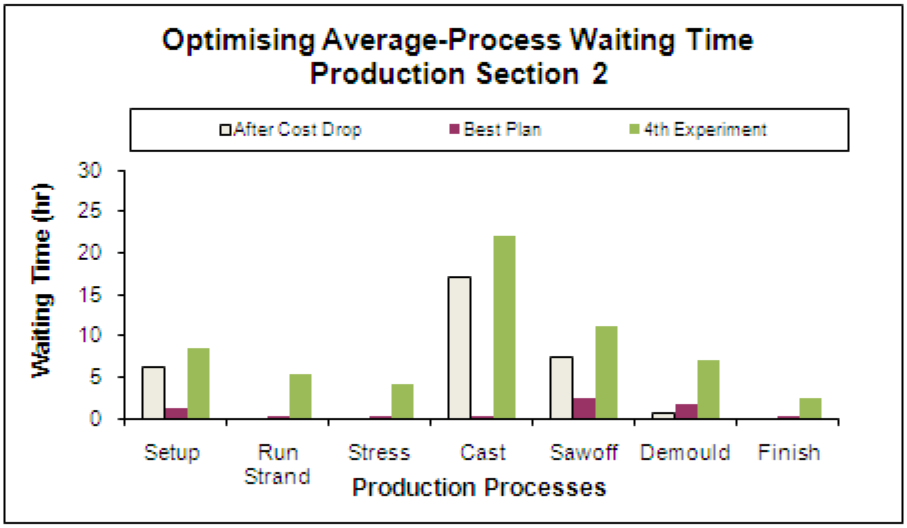


Figure 8.34: The obtained process waiting time after reducing one crew for each of the delayed ('casting', setup', and 'sawoff') processes in production section 2

The availability of a smaller number of crew alternatives assigned for the setup process affected its workflow, as figure 8.34 shows. The limited number of operators available for the 'setup' process resulted in a delay. The crew formation of the casting process required the largest number of operators to carry out the tasks, and hence the limited number of operators available for this process increased the process waiting time for this process and other following processes (sawoff, demould, and finish).

8.5 A COMPARISON STUDY BETWEEN THE PROPOSED MODEL, SIMULATED ANNEALING AND MONTE-CARLO MODELS

In order to evaluate the performance of the proposed GA model, both Simulated Annealing and Monte-Carlo (MC) models were developed.

The Monte-Carlo experiment was designed to start by generating only one set of solutions using a random number generator. This generator selected a crew from each alternative pool associated with a process. After forming an allocation plan in which a crew was proposed for each process, the simulation engine evaluated the generated allocation plan, the results being stored in a database. An allocation plan was generated per iteration to be evaluated by the simulation engine.

The Simulated Annealing model started with a temperature equal to 70 (temperature coefficient =0.7), a decrement of 0.01 (α=0.01) and 20 iterations at each temperature in order to explore the solution space to look for the most promising solutions. Then, a gradual temperature reduction took place in which less randomness in the searching process was achieved as the cooling process started. This type of exploration was achieved using the proposed '*Probabilistic Dynamic Mutation'* operator.

8.5.1 Analysis Crew Allocation Outputs Using Simulated Annealing and Monte-Carlo Techniques

The Monte-Carlo model utilised random allocation costs, as it indicated a better cost reduction than the GA and SA for the first 22 generations/ iterations. The best GA of each generation showed a significant and rapidly improving trend towards the minimum allocation cost. The best SA of 20 iterations under different temperatures indicated a parallel convergence with the GA, but with a slight difference in cost reduction and late cost drop in comparison with GA. Both GA and SA were considered as evolving solutions to identify the best allocation plan, while the Monte-Carlo model utilised the '*Trial-Error*' concept to identify, by chance, the minimum allocation cost.

The proposed GA gave better results compared to the Monte Carlo method for three reasons, the main reason being that the intelligent exploration of solution space requires only the proposed GA; the second reason was that Monte Carlo was found to be computationally expensive before an optimal solution is reached as it depends on a trial and error method rather than orientated algorithms such as GAs. In addition, only unique chromosomes were allowed in the population using a GA, whilst repetition in Monte Carlo cannot be avoided since it is considered as being a totally random technique. Monte Carlo sampling does not give as smooth a cost profile, hence the analysis of such fluctuating profiles is difficult to interpret.

However, applying a Simulated Annealing model gives closer results to the proposed model, except in the case late of the cost drop which can be seen after iteration 31. A promising solution area was explored in this iteration. The cost improvement using SA shows slightly less improvement than that achieved using GAs. The crossover alongside the mutation operator used in the GA can play a vital role in providing more randomness whilst searching the solution space. Figure 8.35 shows the allocation costs yielded through generations/ iterations by using Simulated Annealing, Monte-Carlo Sampling techniques and the proposed GA system.

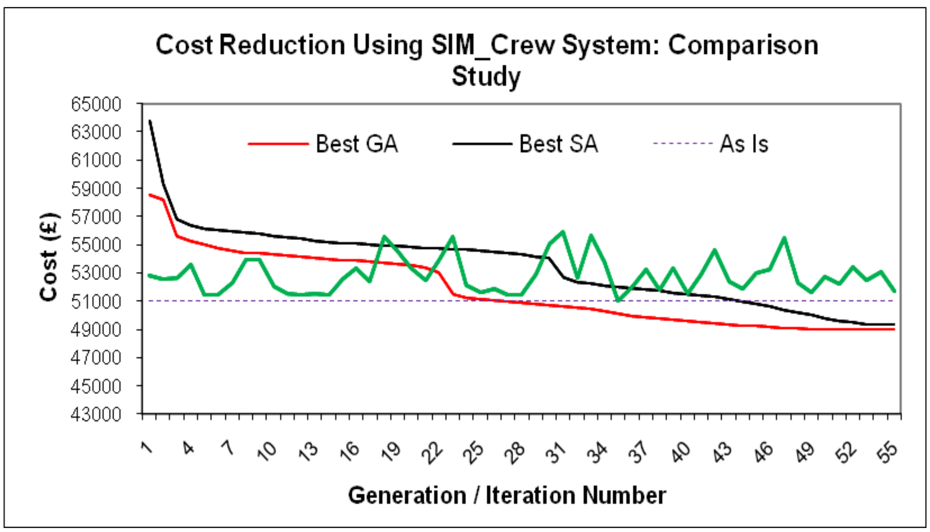


Figure 8.35: Cost comparison using 'SIM_Crew' system: comparison study

It can be noted that the proposed GA model converges faster than other approaches. Through figures 8.1 and 8.3, it was proven that cost was highly dependent on time, direct cost being a function of time. If the utilisation of skilled operator groups (both chargehand and operator) is well balanced, the throughput time can be reduced as lower process-waiting times are achieved, the cost eventually being reduced as a response to such behaviour.

It was interpreted that the behavior of throughput time was similar to that of the cost reduction curve behaviour. The resulting throughput times using GA, SA and MC were identified, and a comparison study was conducted to show the behaviour of throughput time in comparison with the cost reduction curve; figure 8.36 shows the comparison.

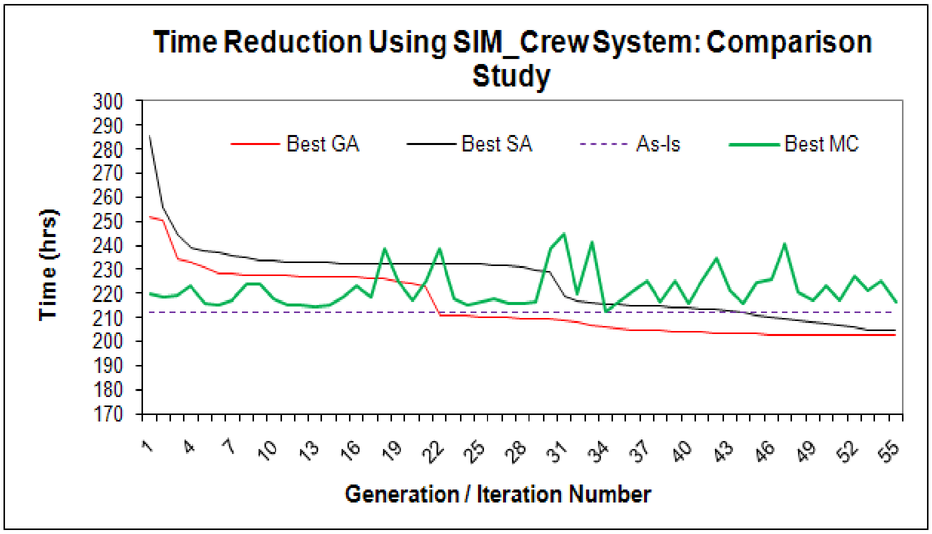


Figure 8.36: Time comparison using 'SIM_Crew' system: comparison study

Figure 8.36 depicts the reduction in throughput times, both random reduction and evolving reduction in throughput times which were identified using Monte-Carlo, SA and GA approaches. The results showed that there was a logical relation between minimising allocation cost and reducing process-waiting time and subsequently the throughput time. Generation 36 outlined that minimising allocation cost resulted in a reduction in throughput time, while generation 48 indicates that a significant high allocation cost results from a high throughput time.

This analysis was considered using the Monte-Carlo approach, as the random behaviour of outputs was found to be useful to the interpreter. It was concluded that both GA and SA approach the minimum allocation cost systematically by evolving solutions, but with a different cost improvement. Monte-Carlo is computationally intensive and repeated solutions can occur during generation of random solutions.

8.6 CHAPTER SUMMARY

In this chapter, the 'SIM_Crew' model was applied and the resulting outputs were discussed. Four scenarios were designed to conduct the required analysis regarding operator utilisation, process-waiting time and their effects on both resource allocation cost and time. The simulation results were compared with the current situation: allocation cost was reduced alongside the optimisation of other resource utilisations as proof of improvement. By using the proposed chromosome structure, the resulting improvement compared with the 'As-Is' scenario determines the efficiency of the proposed structure.

A detailed analysis of operator utilisation for each shift was conducted depending on the skill level of the chargehand/operator alongside the process-waiting time of each production section. The results showed that less involvement of skilled chargehands during night shift was a significant factor in reducing the allocation cost. The synchronised process of allocating resources led to the minimisation of process time for most of the shared resources, especially in production section 2. Casting process-waiting time in this section was reduced significantly which affected the reduction of total allocation cost. A number of experiments to test the sensitivity of the model showed that decision variables, such as number of operators and number of crew alternatives, can significantly affect the performance of the developed allocation model in terms of cost and performance.

Simulated Annealing and Monte Carlo Simulation models were developed for comparison purposes. The GA showed slightly better results in terms of approaching the desired solution. The SA model performed similarly to the GA but it demonstrated different cost reduction behaviour in terms of late cost reduction with slight improvements. The Monte-Carlo simulation model provided the approximate solution by randomly approaching one of the promising solution sets.

CHAPTER 9

SUMMARY, CONCLUSION, AND RECOMMENDATION

9.1 INTRODUCTION

In this research, the integration of simulation with Genetic Algorithms was presented and discussed to develop a crew allocation system. This allocation system was used to allocate a suitable crew of workers to the right process, associated with manufacturing systems in the precast concrete industry. This allocation process enabled optimised worker utilisation, and ensured minimum process-waiting time. The best labour allocation plan, to achieve minimum allocation cost being the ultimate objective of developing an allocation system of this nature.

This chapter summarises a number of highlights concluded from each system component. In addition, the behaviour of system performance was analysed in terms of improvement achieved and its significance to the benefits associated with the proposed system.

9.2 OVERALL CONCLUSIONS OF THE CREW ALLOCATION SYSTEM

The developed simulation model in this study was used to test and identify system performance of each proposed crew allocation plan. The simulation model was successful in that it fully imitated the precast manufacturing system. The simulation tool was capable of capturing all aspects of the labour-driven processes involved within the manufacturing system. All resources (workers + machines) were modelled and assigned according to the process requirement. The developed model imitated the currently adopted scenario successfully, as explained in chapter 6, section 8.1. All bottlenecks and overlaps were resolved by sharing resources and were identified using designed performance criteria.

The parallel-repetitive processes layout of the current precast concrete manufacturing system and the equivalent simulation model design for that layout revealed a limitation in the current software in terms of modelling shift patterns. The design of the current PROCESS module imposed some restrictions such as the availability of all resource to continue a process. The delivery of jobs to the next working shift crew when the available time was insufficient and difficult when using the current module. This type of issue being common, in manufacturing systems, where multiple shift working, is applied to carry out operations on labour-intensive processes.

In order to overcome the resulting limitation caused by the simulation model layout design, a special PROCESS template was developed. The developed module was designed to avoid and resolve any limitation of the current PROCESS module. The scheduled resource pools (three were designed in this module) helped to imitate the labour-intensive process of multi-shift working, each working shift having its own crew of workers for a specific shift time span. This represented a major new innovation which was subsequently adopted by the software designer.

The concept of using a GA in solving this type of problem and the construction of an innovative chromosome to accommodate multi-attribute inputs assisted in solving the complex problem being investigated. The proposed operators contributed significantly in the search for promising solutions within a very large solution space. The selection mechanism of chromosomes played a vital role in selecting promising chromosomes, and provided a greater chance for strong chromosomes to be selected again. The overall structure of the proposed system and the successful integration of its components led this system to be considered as an advanced crew allocation system that can be used to solve complex crew allocation problem in the precast industry.

9.3 CONCLUSION FROM LITERATURE REVIEW

The literature review of previous practices of crew allocation systems developed in a number of labour-intensive industries was useful in identifying the 'state-of-the art' used in solving crew allocation problems. A gap in knowledge was identified through reviewing a number of related crew allocation research contributions. The gap related to a number of issues; one of them being the relationship between allocation cost and other indicators such as resource utilisation and process-waiting time. The literature review was useful in identifying the requirement for a more advanced crew allocation system in the precast concrete industry and to consolidate the developed allocation system with the required theoretical evidence.

9.4 SPECIFICATION AND PROCESS MAPPING DEVELOPMENT

The developed process maps were successfully used to capture the hierarchal structure of the sleeper precast concrete manufacturing system. The relationships among all labour-driven production processes were identified by developing IDEF0 diagrams. These diagrams were successfully used to capture all restrictions and resources used to carry out each production process besides all input and output elements of the precast concrete manufacturing system. In addition, these diagrams were useful in providing the required logic of each process and the overall process relationships required in the simulation modelling phase.

9.5 DATA COLLECTION

Data collection phase was essential in order to provide the developed simulation model with the required amount of inputs. Data collection tools such as structured interviews, and onsite visits were used in order to capture the required data. The collected data was used to imitate the "As-Is" crew allocation scenario. Other data such as the crew alternatives available for each process operation was identified by the production manager, according to his/her experience. This practical knowledge was used in the improvement scenarios through manipulating and proposing a combination of different crew alternatives available for each labour-driven process.

9.6 SIMULATION MODELLING

The sleeper precast concrete manufacturing system was imitated successfully by developing a process simulation model. The simulation model involved production processes, physical resources, and allocated workers. The input of the simulation model was identified through a number of data collection techniques and the output was useful to test the current "As-Is" crew allocation plan applied in the sleeper production system. The developed simulation model outputs reflected successfully outputs of the current crew allocation scenario. This enabled the simulation model to test and provide performance criteria for any other feasible crew allocation plans.

9.6.1 Process Template Modelling

Due to the existence of a parallel repetitive production processes layout in the precast production system, a limitation in the current PROCESS module was apparent.

The limitation in the current PROCESS module available in the basic process library of the simulation software used was identified. This limitation appeared while simulating multi-shift crew allocation processes in multi-parallel repetitive production processes.

This limitation resulted in overflow resource utilisation while simulating the repetitive processes involved. In order to overcome the modelling of multi-shift crew allocation process problem and to remove the modules' limitation, a special PROCESS template module was developed. The module was verified within a simple simulation model and then a larger simulation model. The resultant resource utilisation obtained using the newly developed PROCESS module was proven to be accurate.

9.6.2. 2D and 3D Simulation Visualisation Aspects

The 2D-visualisation aspect of the developed simulation model was made using the relevant modules available in the ARENA animation library. The 2D-animation version of the developed simulation model was useful in verifying the developed simulation model and to animate production system's reaction while evaluating a crew allocation plan.

The 3D-visualisation model was created using 3D ARENA Player. The developed visualisation model was useful in exploring the precast concrete production system and to navigate the production processes. The developed dashboard in conjunction with the visualisation facility provided a powerful means of animating performance criteria and the work progression at each simulated process step.

9.7 DEVELOPMENT OF THE OPTIMISATION MODULE

In order to increase searching capability of the developed simulation model, an optimisation module was developed. The optimisation module was designed to be embedded within the simulation model for improved searching capability. This module was based on the evolutionary concept provided by Genetic Algorithms in order to explore more promising solutions in a large solution space.

The modelling simplicity in the Genetic Algorithms and the ability to handle the complexity of testing associated with more than one crew allocation plan was the reason of selecting GAs as an optimisation module. The flexibility available in GA operators confirmed to be a convenient tool for modelling such complex allocation problems.

9.7.1. Chromosome Structure

The chromosome concept in Genetic Algorithms was useful in storing all decision variables (crew alternatives). The flexibility of the chromosome structure enabled tailoring to involve more than one layer. Each layer was successfully used to store the same attributes of crews of workers. This multi-layered structure enabled storing different sets of data in a consistent manner to enable retrieval when required.

9.7.2. Selection Rule

The “Class Interval” selection rule was developed to give more chance for promising chromosomes to be selected again. The developed algorithm provided the flexibility and simplicity to code the selection rule of this part of the algorithm.

9.7.3. Probabilistic Dynamic Crossover

Probabilistic Dynamic Crossover (PDC) was developed to ensure the required randomness effect in each pair of chromosomes. The probabilistic nature of PDC was necessary to swap vertically a random number of genes between each selected pair. As an extra source of randomness and to avoid duplications in the tested chromosome Probability Dynamic Mutation (PDM) was developed.

9.7.4. Probabilistic Dynamic Mutation

In PDM, a random number of genes were selected for an individual. The selected genes were mutated by the available list of crew alternatives for each gene. The random genes manipulation using Monte Carlo sampling was an extra source of randomness which led to a continuous improvement and the investigation of more promising solution areas.

9.7.5. General Notes

The GA enabled a comprehensive evaluation of the simulated sleeper concrete production system performance under different allocation plans. The relationship amongst the resulting allocation cost, utilisation of resource and process-waiting time was successfully identified.

The optimal allocation cost was identified using the proposed optimisation engine. An 4.295% allocation cost reduction was achieved. In addition, an optimal crew allocation plan was identified to ensure the best utilisation balance and minimum process-waiting time.

The reduction rate achieved in average process-waiting times in production section 1 was 44%. This reduction was achieved after running the 'SIM_Crew' allocation system which identified the best allocation plan after a number of generations. In addition, a 68.75% reduction in average process-waiting time in production section 2 was achieved. This significant reduction in process waiting time played a key role in minimising the labour allocation cost. An Industrial feedback was provided regarding the developed allocation system and its applicability in manufacturing systems, see *appendix K*.

9.8. CONCLUSION OF VERIFICATION AND VALIDATION

The developed simulation model was verified and validated as a reliable crew allocation system. The verification and validation processes of the developed allocation system proved that the developed system was simulating precisely the "As-Is" allocation plan and reflected the actual system. In addition, all system resources were captured successfully in the developed simulation model.

9.9 COMPARISON WITH OTHER TECHNIQUES

The resulting outputs of the proposed simulation-based genetic algorithm allocation system were compared with other searching tools such as Monte-Carlo (MC) sampling technique and Simulated Annealing (SA) optimisation rule. The MC and SA searching rules were developed and embedded within the same simulation model as optimisation modules to identify the best allocation plan. The comparison results showed that the GA outperformed other searching rules in terms of reaching optimality of both cost and time in a shorter time than SA. The second best optimisation module was SA followed by MC.

9.10 RESEARCH CONTRIBUTION

The research conducted provided a number of advantages contributing both to the precast industry and knowledge associated with labour intensive industries in general.

9.10.1 Contribution to the Precast Industry

The labour allocation problem is frequently faced by precast manufacturing operations. The 'SIM_Crew' allocation system can be used to advance the practice of labour allocation processes in such industry. The main deliverable of developing such an allocation system was addressed by providing a computerised allocation system that enables precasters to optimise their labour allocation plan in the shortest processing time.

The consumption of less human effort in such process extends the opportunity for wider exploration of several feasible allocation plans to be evaluated in a reasonable time. In order to enable the precasters to be familiar in using such allocation system, comments and suggestion were provided to the precast industry, see *appendix M*.

The proposed allocation system provides solutions or supporting allocation plans for improving labour-intensive resource utilisation. Allocation cost reduction can be achieved through optimising resource utilisation, minimising process-waiting time and subsequently the overall throughput time. This reduction guarantees a better workflow, reduces customer lead-time and subsequently the number of tardy/late jobs. The benefits of adopting the proposed crew allocation system in the precast industry are addressed in *appendix N*.

9.10.2 Contribution to knowledge

The main contribution of this research is the methodology to integrate simulation technology and Genetic Algorithms to solve crew allocation problems in labour-intensive processes. The system prototype was developed to demonstrate the implementation of the proposed methodology. The system applied database integration, simulation modelling and Artificial Intelligent techniques (a GA was used in this research for the aforementioned reasons in chapter 2, section 2.3.7). It helped precasters to solve the complex crew allocation problem in their manufacturing systems.

The formulation of a crew allocation system in a repetitive-parallel processes layout which can be seen in most precast manufacturing systems by using Simulation-based Genetic Algorithms modelling advances the current allocation tools and techniques by providing a different modelling methodology to solve such problems. The development of Multi-Layered chromosome and the ability to handle more than one type of input assisted in suggesting a different way of accommodating variable attribute inputs. In addition, the proposed selection rule was designed by the adoption of a methodology used in another field of application (descriptive statistics). Such adoption enabled knowledge sharing with other statistical concepts to build and design an advanced allocation system.

9.11 LIMITATIONS OF THE DEVELOPED ALLOCATION SYSTEM

In the proposed allocation system, a number of limitations arose when developing the system and applying it in the allocation process. The first limitation environmental impact was not considered in any crew allocation plan as the developed allocation system was designed to allocate crews to processes in a job-shop, a closed off-site environment. The inability to deal with unexpected situations such as worker absence or machine breakdown can be considered as a second limitation. The short term planning ability provided by the developed allocation system depends on the availability of crew alternatives available for each production process.

9.12 RECOMMENDATIONS FOR FURTHER STUDY

1. Different levels of priority for each production process can be included when designing the chromosome. This priority may include more working shifts, different priorities allocated for each process, etc.

2. A more detailed process simulation model can be built in order to capture the required level of process detail. In this case, simulation can be used to capture the detailed duties involved within a process. This type of detailed modelling can provide an insight into how each worker carries out his job within his crew.

3. A worker set concept can be used to carry out activities. More than one worker may be modelled to do the same job at different efficiencies; this applies where resources are shared, with the potential of achieving the best combination to accomplish the work with minimum disturbance.

4. Heuristic rules can be used to model such allocation models: other AI tools can be used in the modelling of a crew allocation system, depending on which facilities the tool can provide to solve such problems.

5. Daily allocation of crews still needs further investigation for better planning. In this case, a different crew can be assigned daily in response to worker availability.

6. Multi-objective optimisation is still worthy of consideration in solving this type of allocation problem. Different costs can be considered as multi-objectives in order to minimise each of them in a satisfactory way.

7. Fuzzy crew processing time might be considered in a further study. A fuzzy model could be developed to be coupled with the simulation model or a mathematical model depending on the suitability of modelling.

8. Other random circumstances may be considered, such as worker absence, delay, or normal leave. This kind of randomness requires a quick response to substitute the absent worker with an alternative. This model could work as a real time crew allocation system.

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APPENDICIES

Appendix A: List of Publications

The following are the publications arising from the research work presented in the thesis:

Journal Papers

[1] Al-Bazi, A. and Dawood, N. (2010). "Developing Crew Allocation System for Labour Intensive Industries Using Genetic Algorithms". Journal of Computer-Aided Civil and Infrastructure Engineering. 2010 can be accessed at: http://www3.interscience.wiley.com/journal/121540141/issue?CRETRY=1&SRETRY=0. (accessed April 2010).

[2] Al-Bazi, A. and Dawood, N. (2010). "Improving performance and the reliability of off-site pre-cast concrete production operations using simulation optimisation". Journal of Information Technology in Construction. 2010 can be accessed at: http://www.itcon.org/cgi-bin/works/Show?_id=2010_25. (accessed July 2010).

Conference Papers

[3] Al-Bazi A. & Dawood N. (2010). Crew allocation modelling using 3d-simulation based simulated annealing. 10th International Conference on Construction Applications of Virtual Reality CONVR 2010. Sendai, Miyagi, Japan November 4-5, 2010. (Accepted).

[4] Al-Bazi A. & Dawood N. (2010). A Multi-Layer Genetic Algorithm for Solving Crew Allocation Problem in the Precast Industry. The 16th International Conference on Automation & Computing, University of Birmingham, Birmingham, UK, 11 September 2010. (Accepted).

[5] Al-Bazi A. & Dawood N. (2010). Simulation Modelling and Multi-Layer Genetic Algorithms to Identify Optimal Crew Allocation in the Precast Industry. The International Conference on Computing in Civil and Building Engineering-2010. June 30-July 2, 2010, University of Nottingham.

[6] Al-Bazi. A., Hedayati, H., Dawood, N., and Dean, J. (2010). Scheduling in a Multi Precast Concrete Production Sections Using Simulation Technology. 20th International Conference of Flexible Automation and Intelligent Manufacturing and Services. July 12-14, 2010, California State University.

[7] Al-Bazi. A., Hedayati, H., Dawood, N., and Dean, J. (2010). A Simulation Model for Identifying Impacts of Order and Resource Selection Rules on Precast Concrete Production Performance. The 20th International Conference of Flexible Automation and Intelligent Manufacturing and Services. July 12-14, 2010, California State University.

[8] Al-Bazi, A., Dawood, N. and Dean, J. (2009). “Development of 3D-Simulation Based Genetic Algorithms to Solve Combinatorial Crew Allocation Problems”. Proceedings of the 9th International Conference on Construction Applications of Virtual Reality. pp. 207-216.

[9] Al-Bazi, A., Dawood, N. and Khan, Z. (2009). “Development of Hybrid Simulation and Genetic Algorithms System for Solving Complex Crew Allocation Problems”. Proceedings of the CIB W078 Managing IT in Construction, October, 2009,Istanbul, Turkey.

[10] Dawood, N. and Al-Bazi, A. (2009). “Enterprise simulation of the precast concrete manufacturing industry“. Proceeding for CIB-W78 25th International Conference, 15th – 17th July, Santiago, Chile.

[11] Dawood, N. and Al-Bazi, A. (2009). “Solving Complex Crew Allocation Problems in Labour-Intensive Industries Using Genetic Algorithms”. Proceeding for Flexible Automation and Intelligent Manufacturing- FAIM 2009, 6th-8th July 2009, Teesside, UK, pp. 1340.

[12] Al-Bazi A. and Dawood N. (2009). “Developing a crew allocation system for labour-intensive process industries using Genetic Algorithms-based Simulation Modelling”. Proceedings of the annual research day and postgraduate symposium 2009, University of Teesside, UK; 05/2009

[13] Dawood, N. and Al-Bazi, A. (2009) "Using Genetic Algorithms to Improve Crew Allocation Process in Labour-Intensive Industries”. The 2009 ASCE Workshop on Computing in Civil Engineering, Texas, Austin, p166-175.

[14] Al-Bazi, A. and Dawood, N. (2009). “A decision support system for pre-cast concrete manufacturing planning: An innovative crew allocation optimiser”. Proceedings of the 2009 CSCE International Conference on Computing in Civil Engineering, Canada, GC 147.

[15] Dawood, N. and Al-Bazi, A. (2008). “Development of an intelligent manufacturing management simulation model: An application to the precast concrete industry”. Proceeding for intelligent computing in engineering (ICE08) international conference, 2nd-4th July, Plymouth, UK, pp. 339-349.

[16] Al-Bazi A. and Dawood N. (2008). “Developments of an Intelligent Production Processes Simulation Model: An Application to the building components manufacturing industry”. Proceedings of the annual research day and postgraduate symposium 2009, University of Teesside, UK; 05/2008

[17] Al-Bazi, A. and Dawood, N. (2008). “Development of an intelligent manufacturing management simulation model: An application to the precast concrete industry”. ARCOM/ Construct IT Workshop, 14th March, University of Salford, Manchester, UK.

[18] Dawood, N. and Al-Bazi, A. (2006). “Improving the performance and reliability of construction supply chain using simulation: a case study for doorsets manufacturing - DOORSSIM-“. Proceeding for CIB-W78 25th International Conference, 15th – 17th July, Santiago, Chile, pp. 483-490.

Appendix B: Types of Production System Layouts

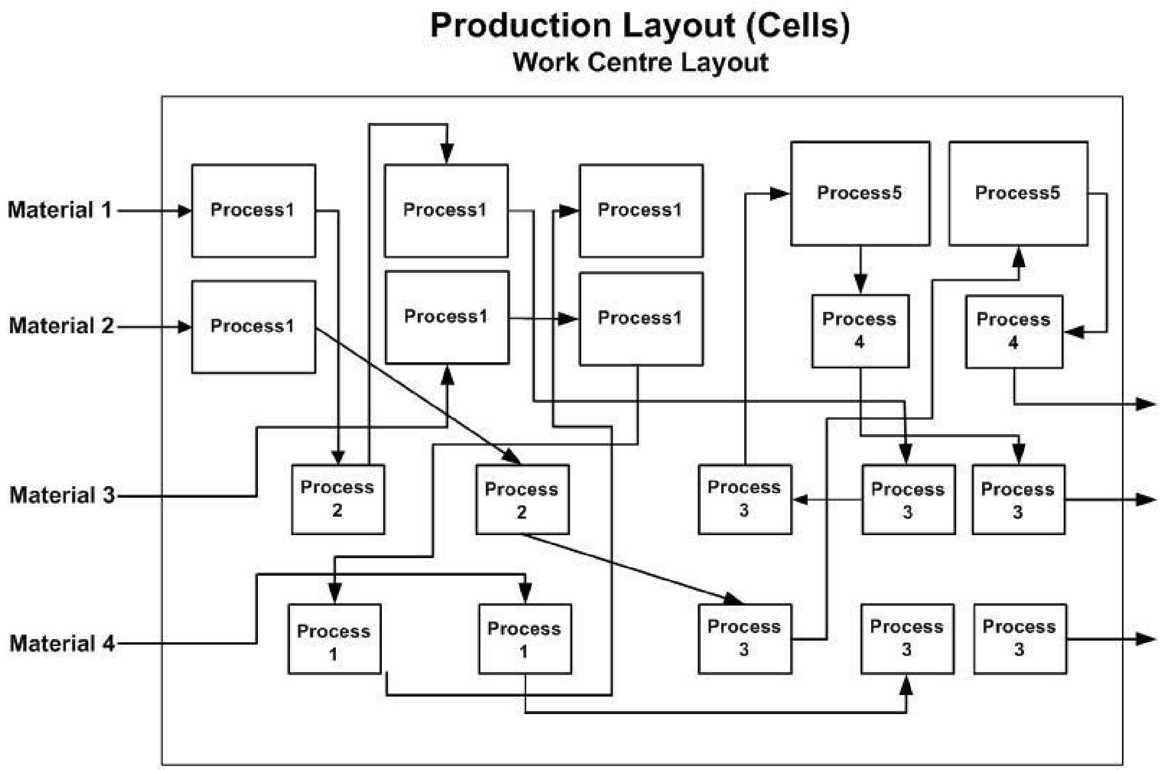


Figure B.1: depicts the layout of the work centre production system

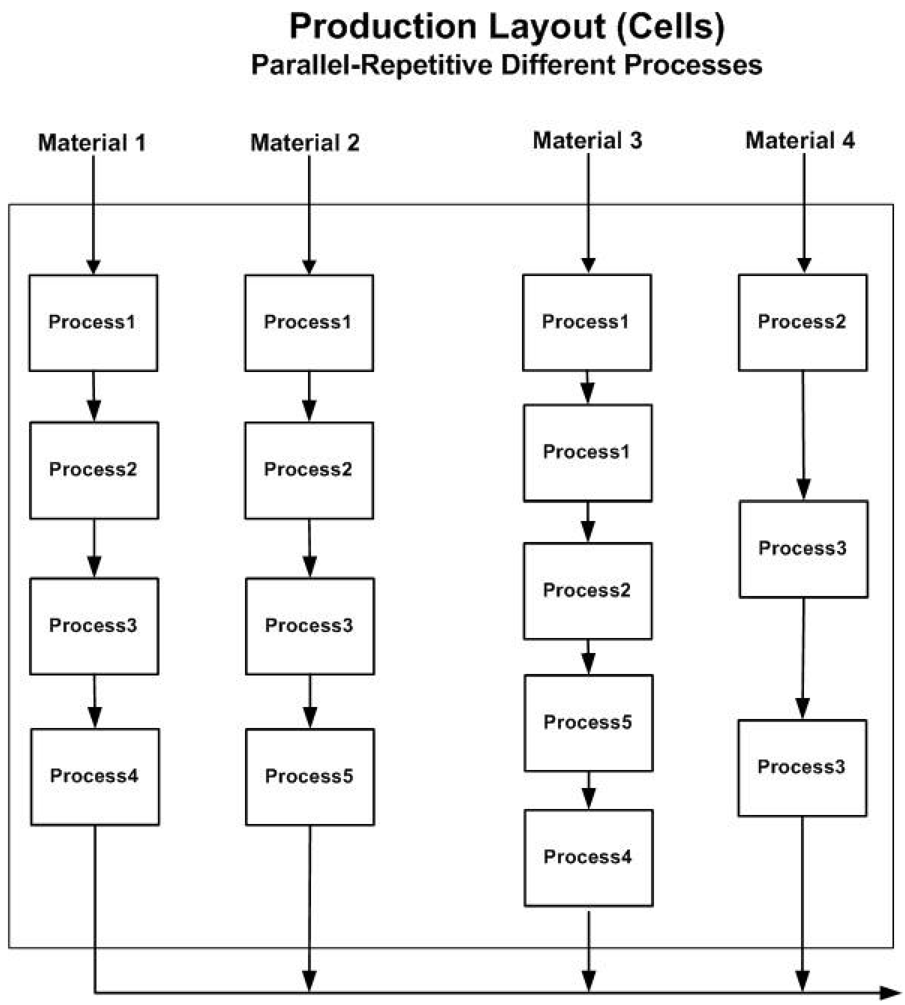


Figure B.2: depicts parallel-repetitive different production system layout

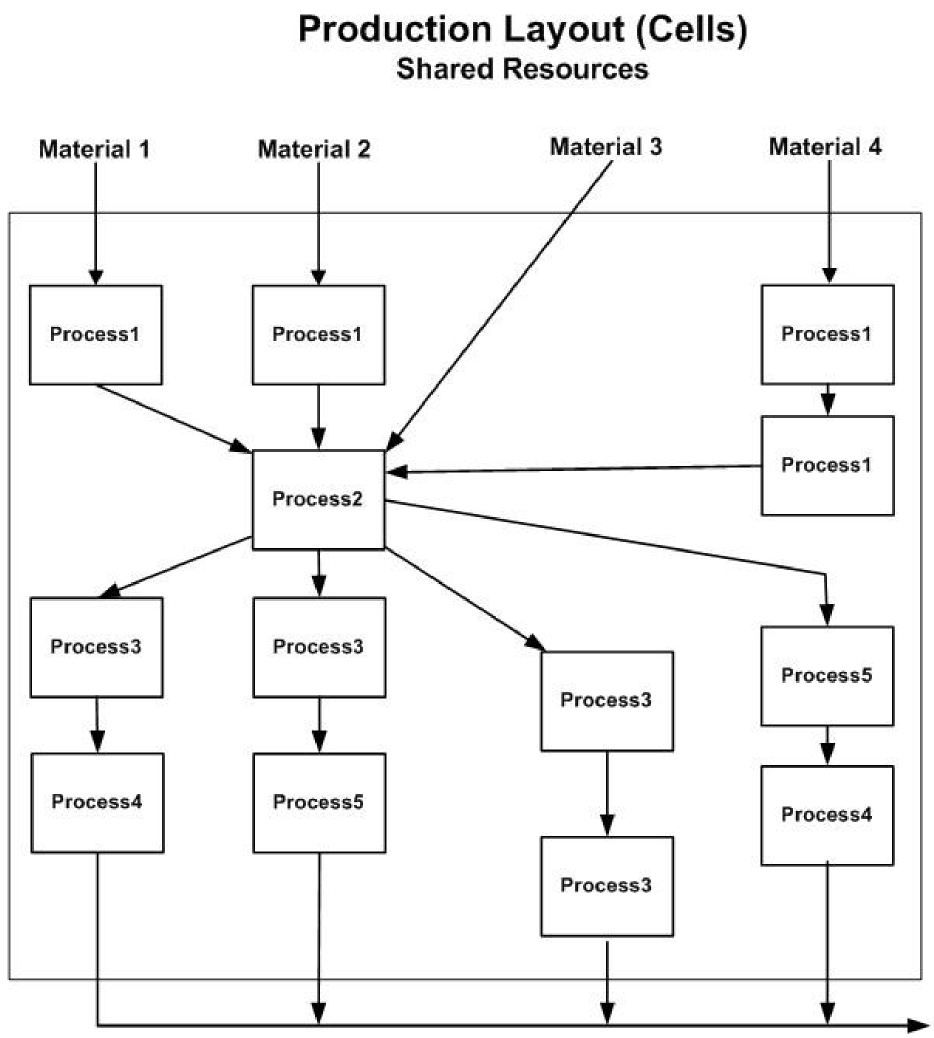


Figure B.3 depicts parallel shared resource production system layout

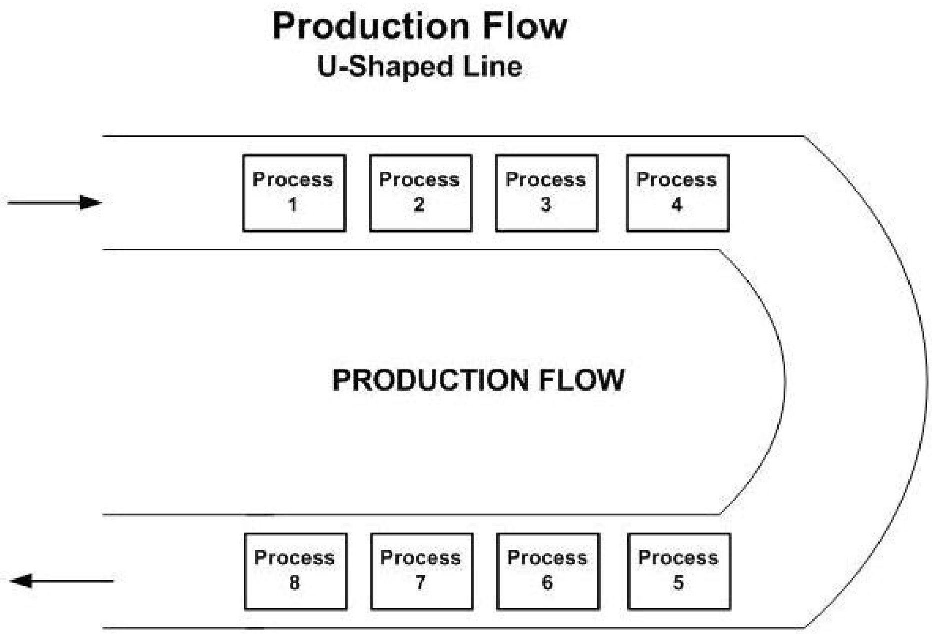


Figure B.4 depicts "U-Shaped" Line Production System Layout

Appendix C: Data Methodology Applied in Company A

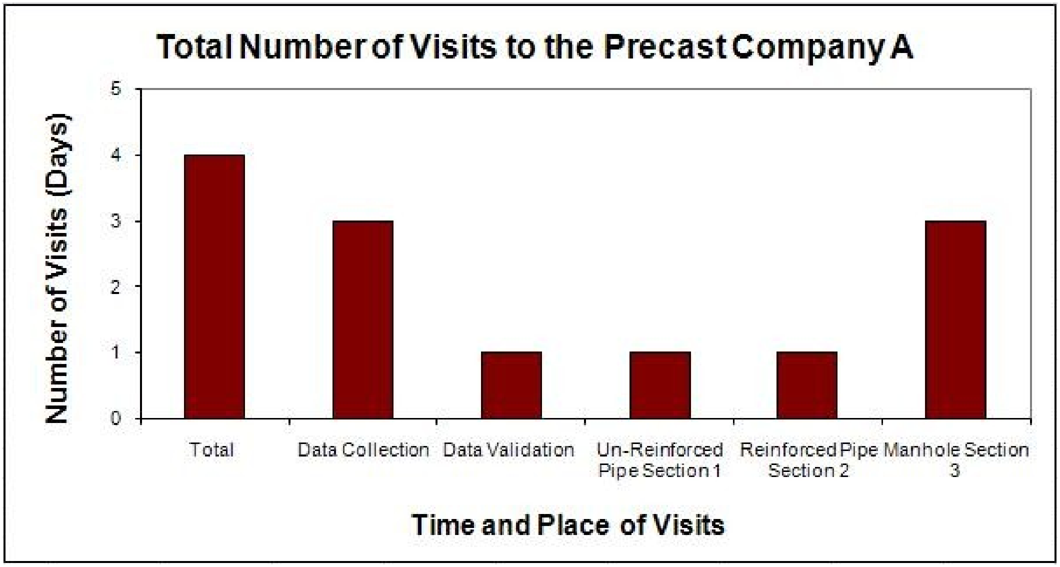


Figure C-1: total number of visits to the precast company A

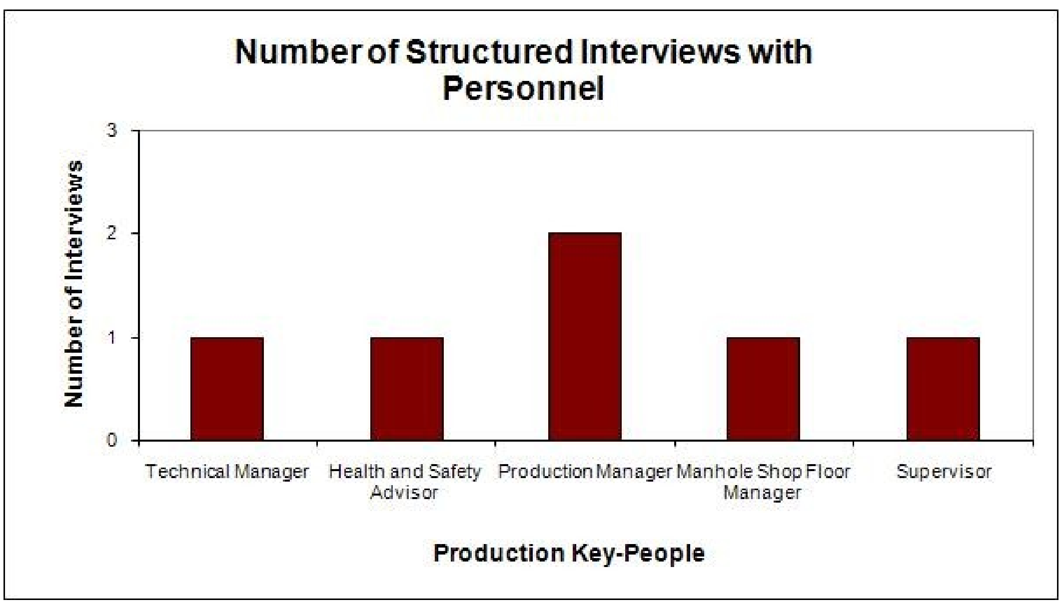


Figure C-2: total interviews with key personnel at company A

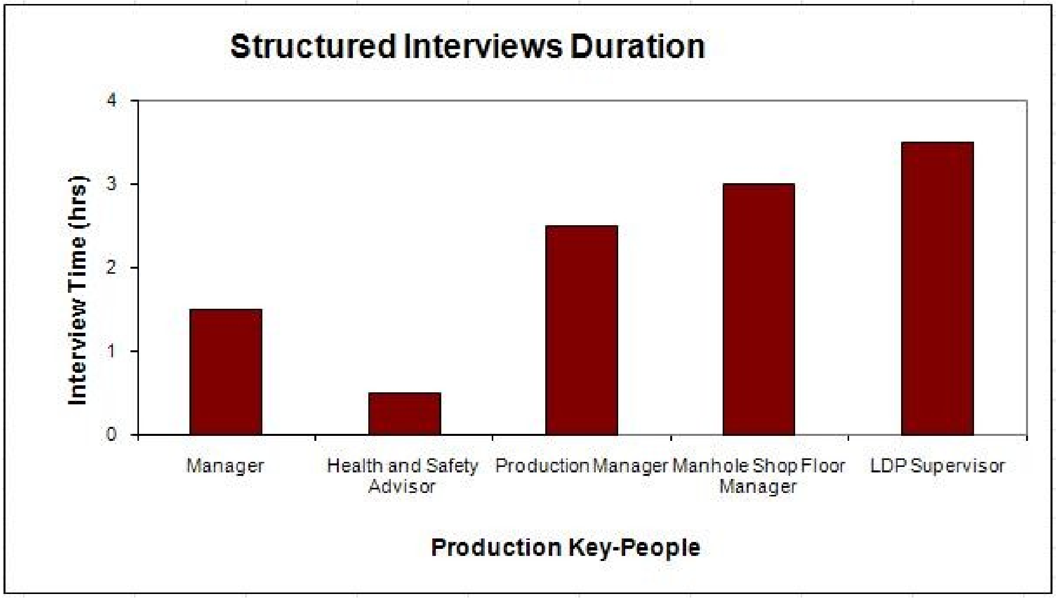


Figure C-3: total interview time spent at company A

Appendix D: Data Methodology Applied in Company B

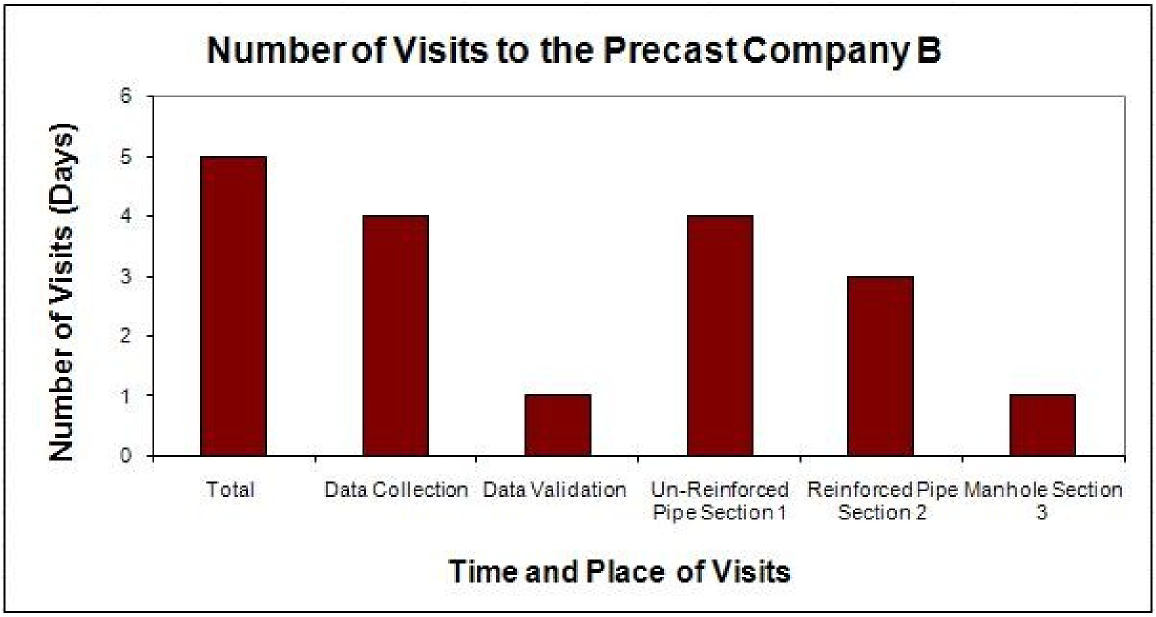


Figure D-1: total number of visits to the precast company B

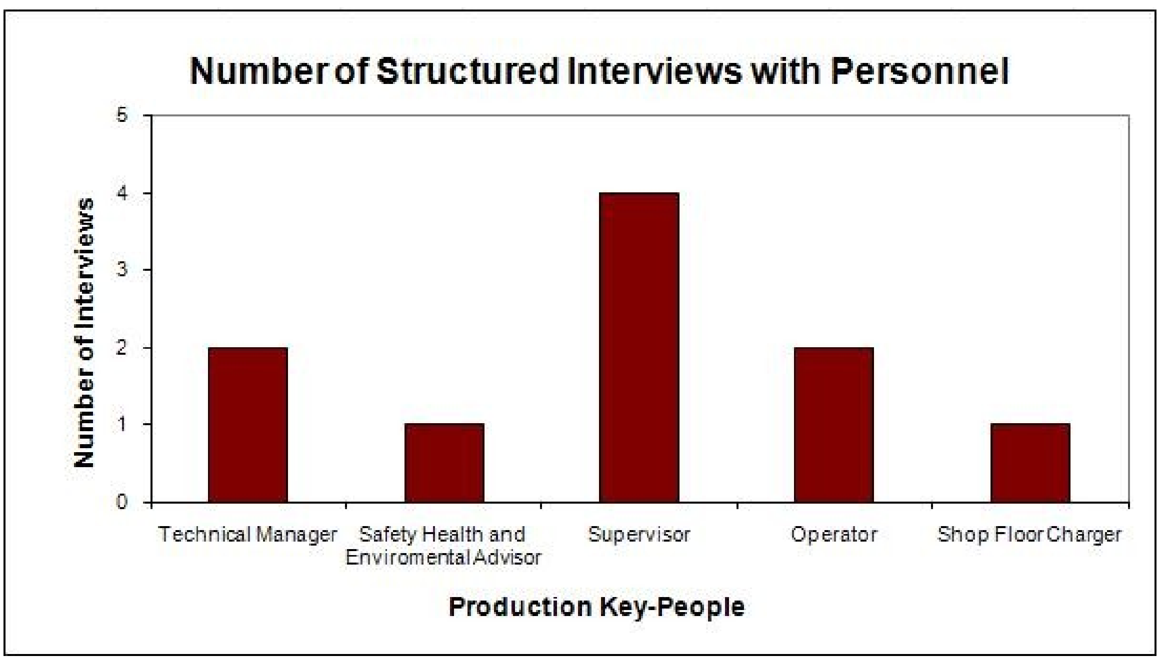


Figure D-2: total interviews with key personnel at company B

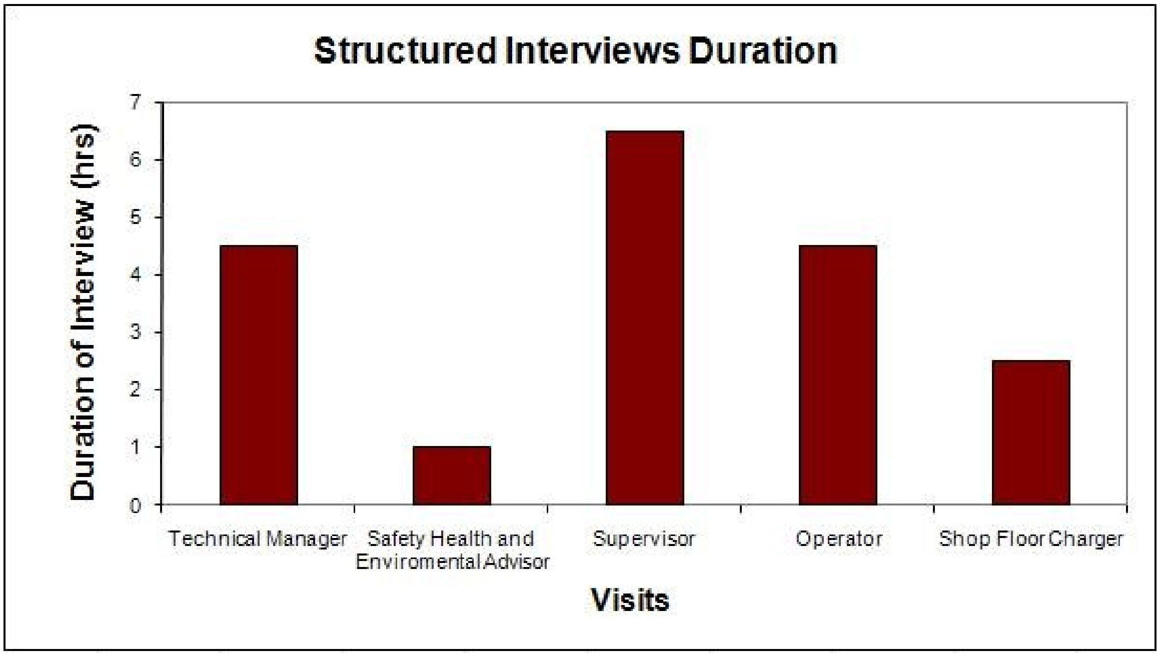


Figure D-3: total interview time spent at company B

Appendix E: Data Methodology Applied in Company C

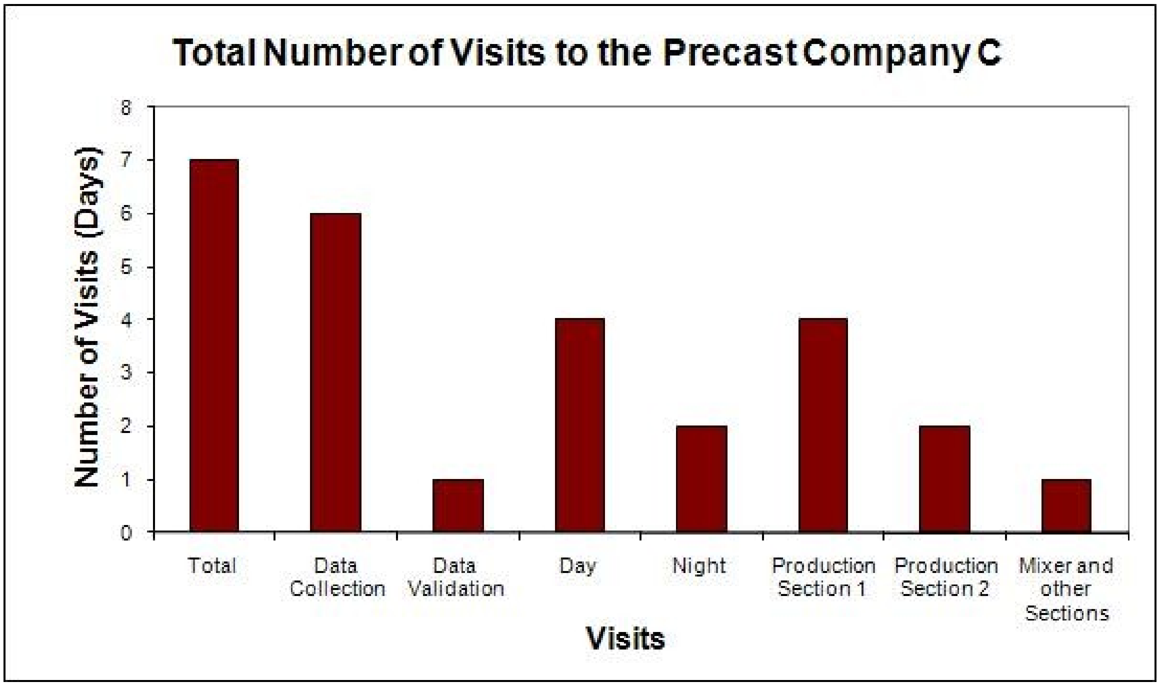


Figure E-1: total number of visits to the precast company C

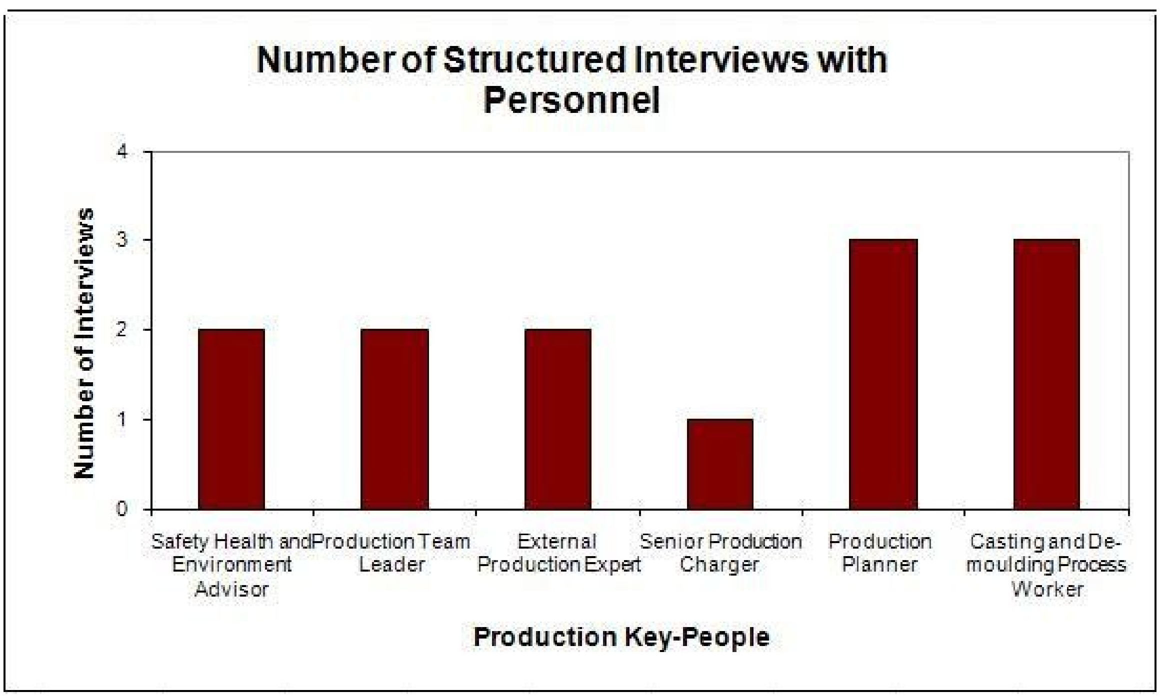


Figure E-2: total interviews with key personnel at company C

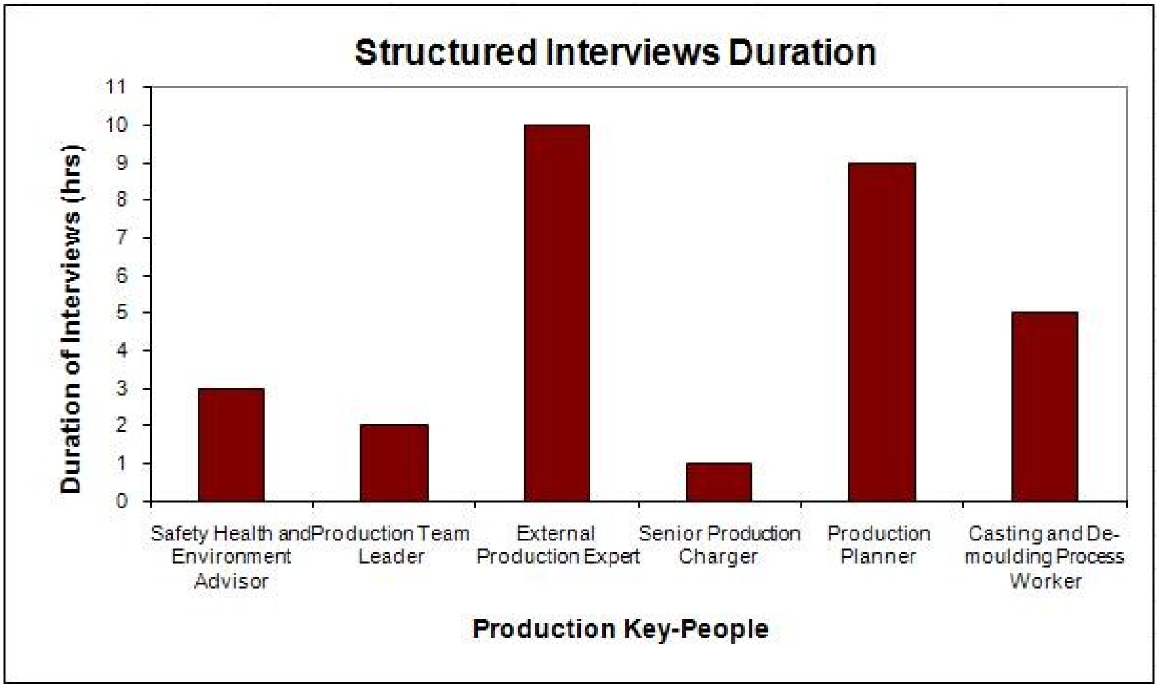


Figure E-3: total interview time spent at company C

Appendix F: Business Process Maps Developed for Companies A,B, and C

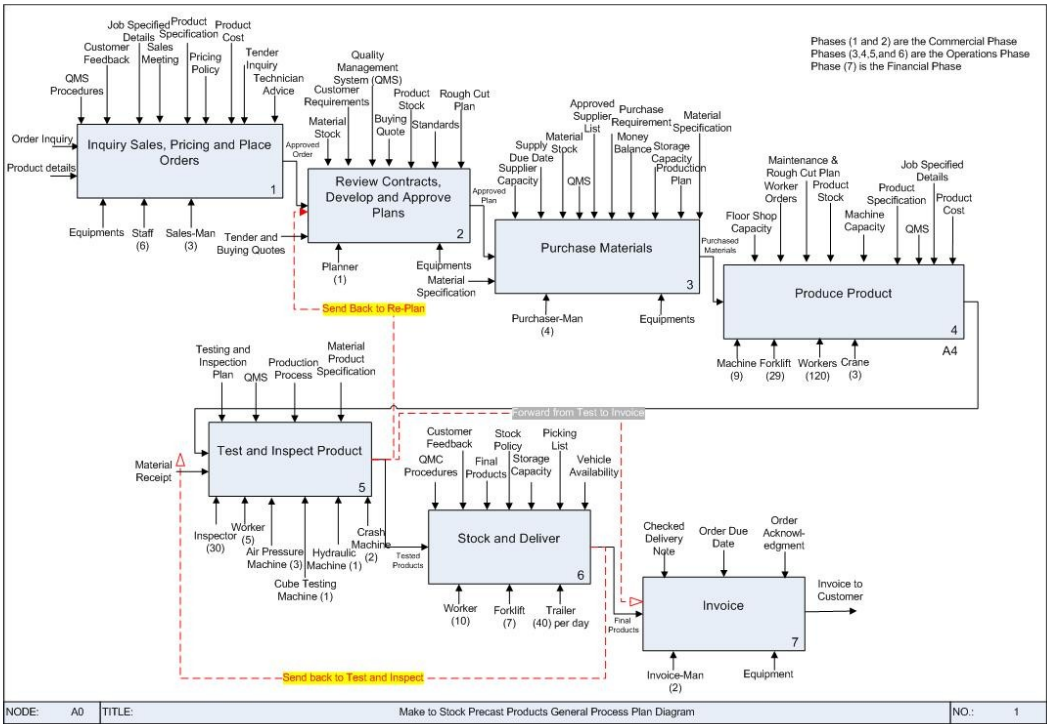


Figure F-1: Business process mapping diagram for Company A

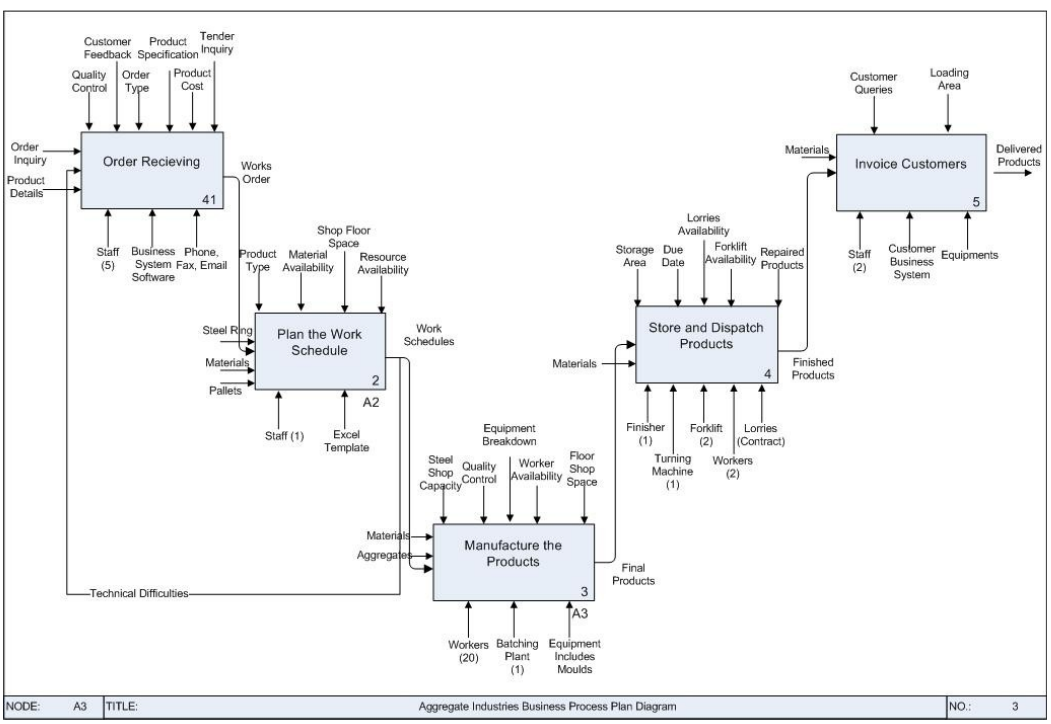


Figure F-2: Business process mapping diagram for Company B

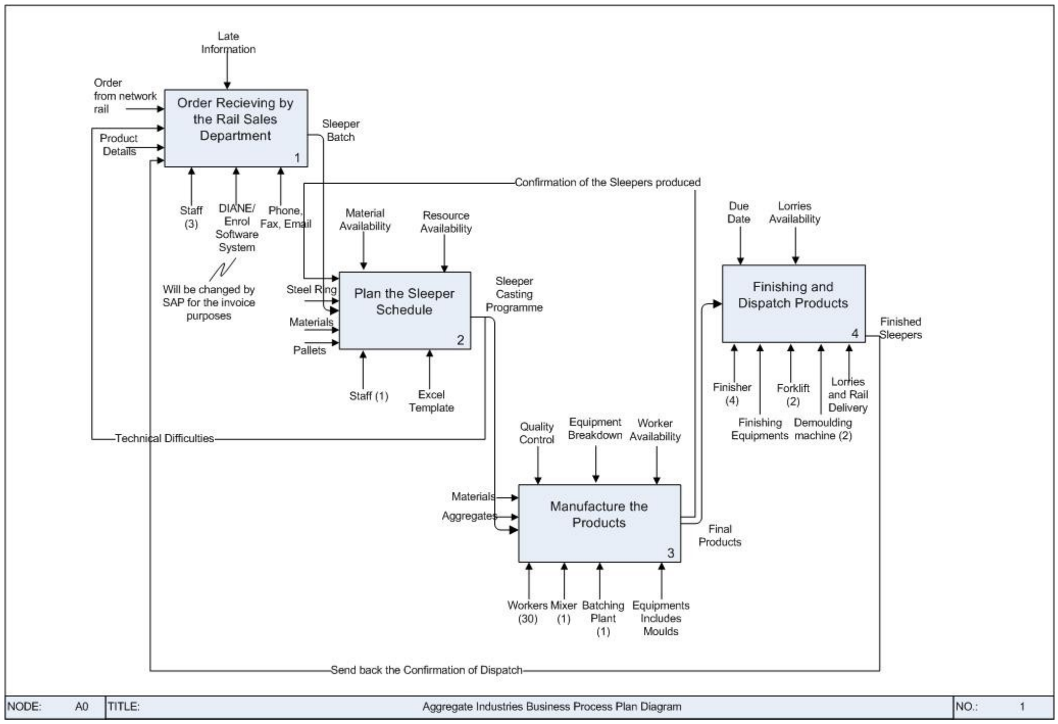


Figure F-3: Business process mapping diagram for Company C

Appendix G: IDEF0 diagrams for Company A, B, and C production sections

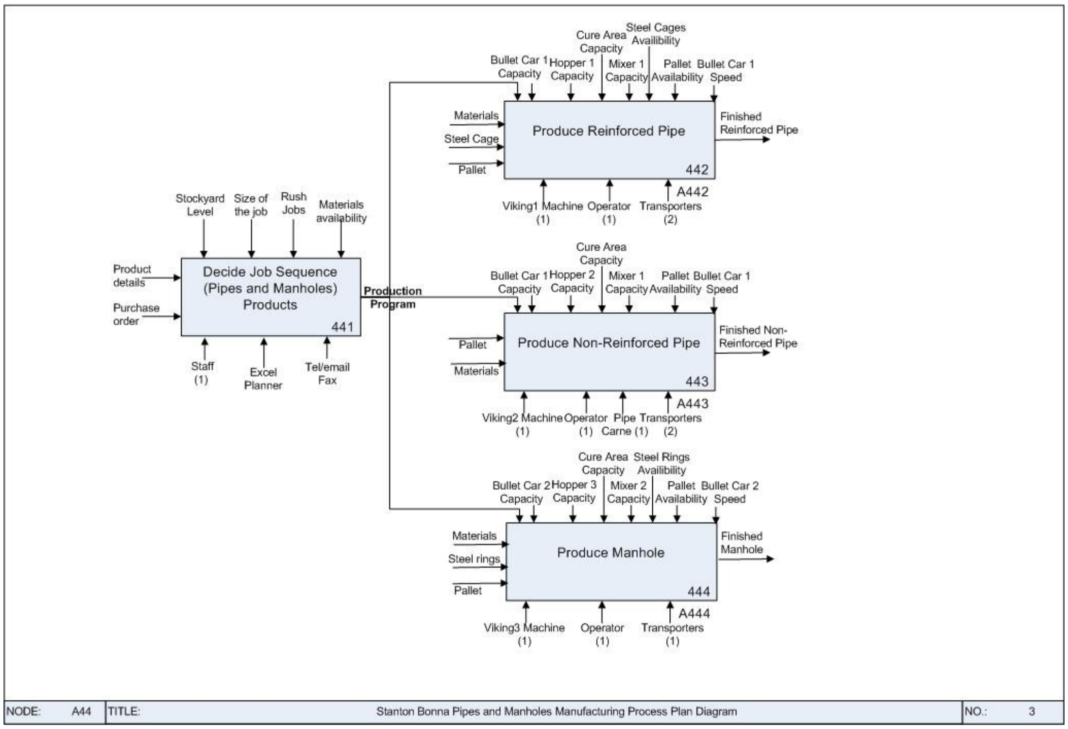


Figure G-1: IDEF0 diagram for the Company A precast concrete production sections

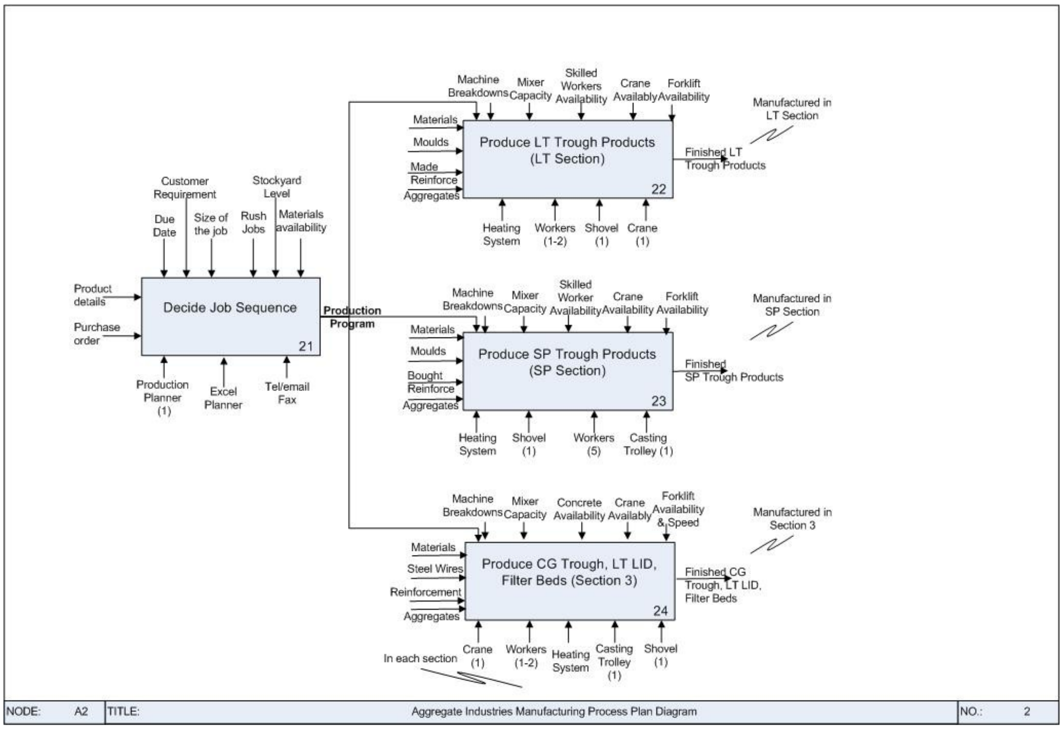


Figure G-2: IDEF0 diagram for the Company B precast concrete production sections

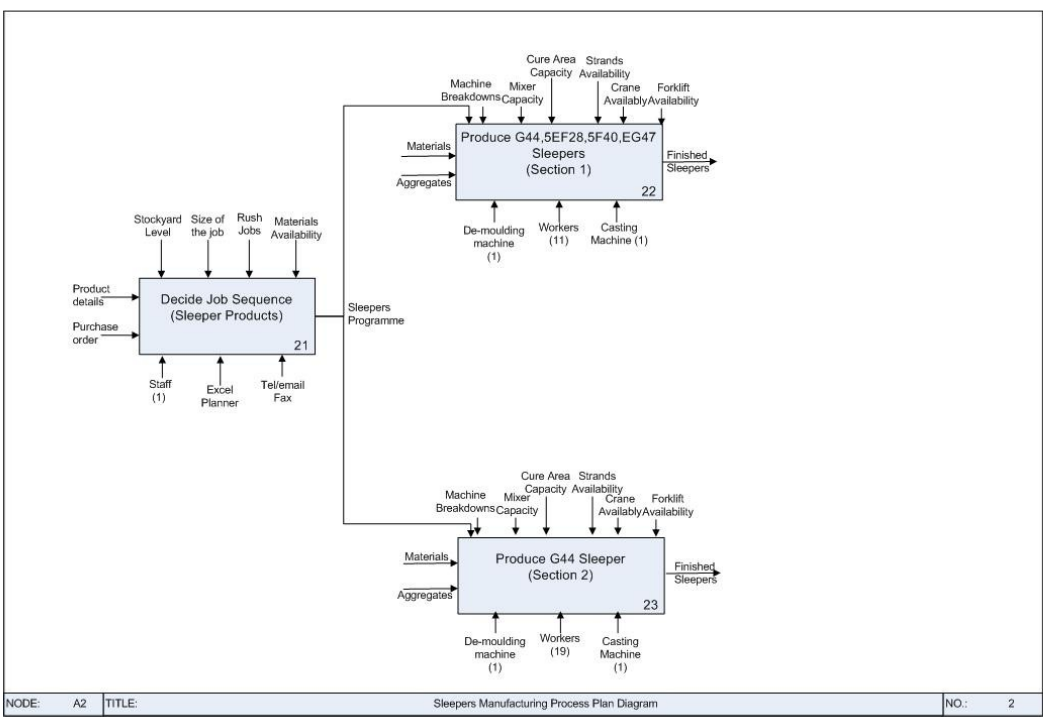


Figure G-3: IDEF0 diagram for the Company C precast concrete production sections

Appendix H: Process mapping diagrams of Company A, B, and C manufacturing systems

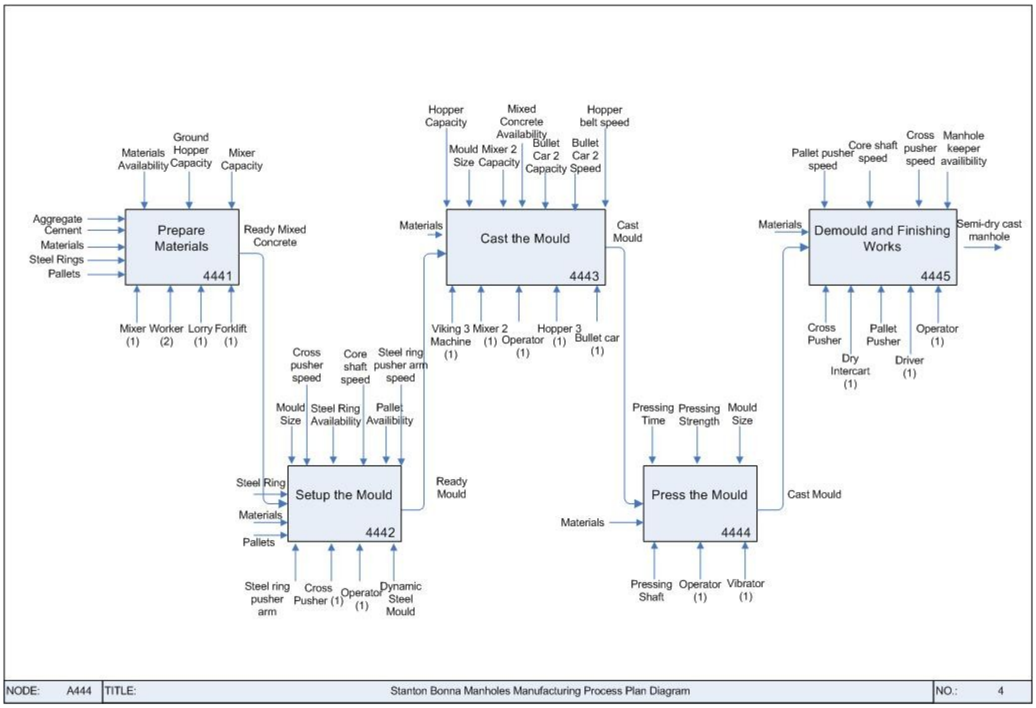


Figure H-1: process mapping diagram of precast concrete manufacturing system in company A

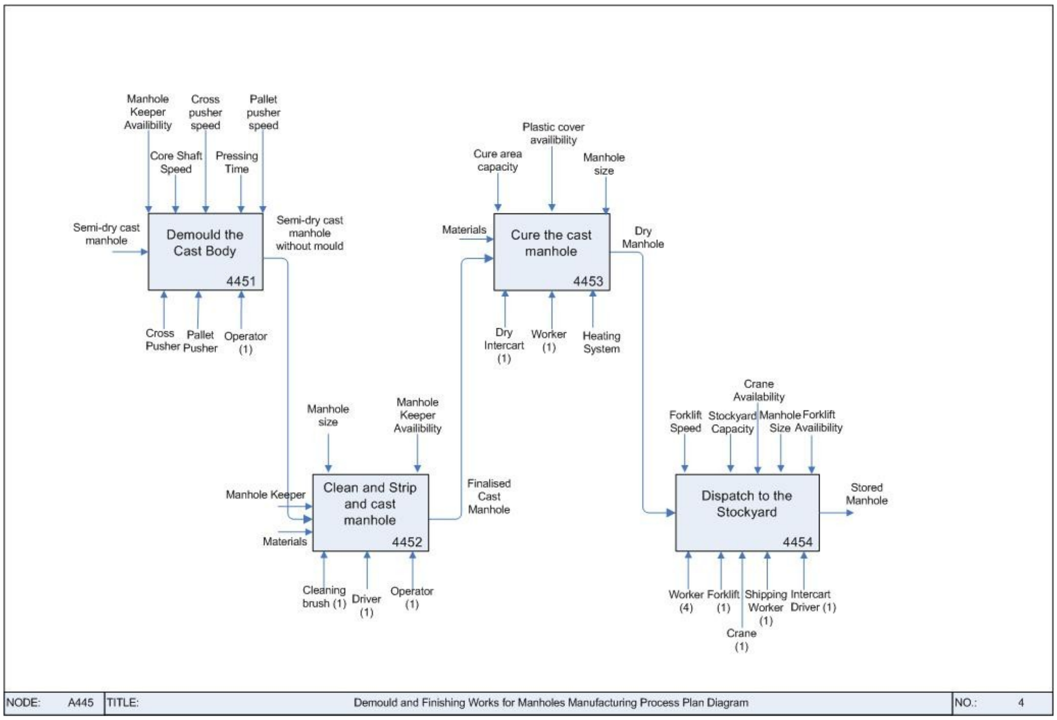


Figure H-1.1: process mapping diagram of precast concrete manufacturing system in company A (Cont)

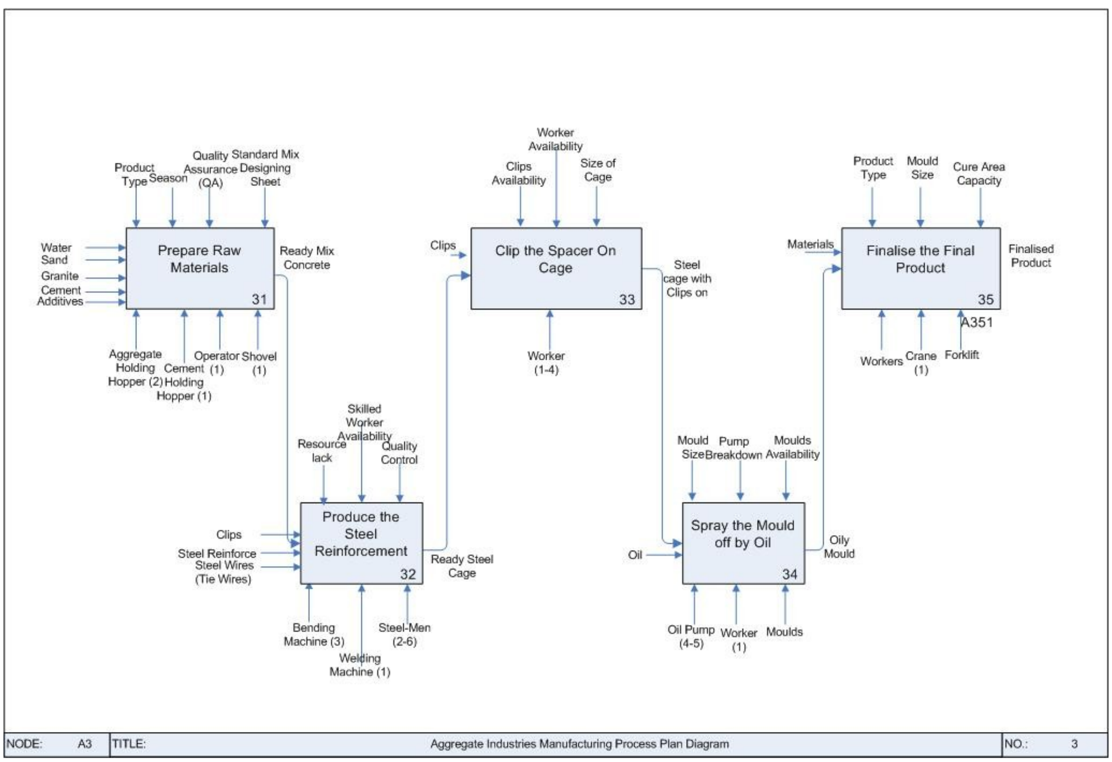


Figure H-2: process mapping diagram of precast concrete manufacturing system of company B

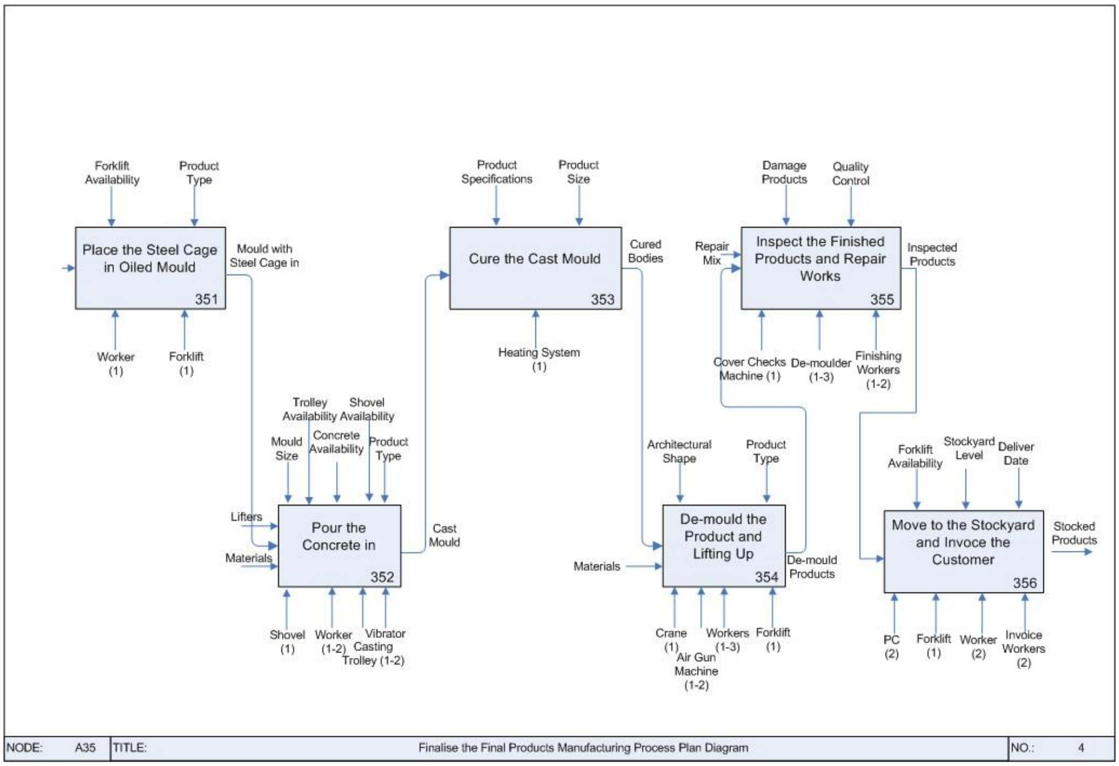


Figure H-2.1: process mapping diagram of precast concrete manufacturing system of company B (Cont)

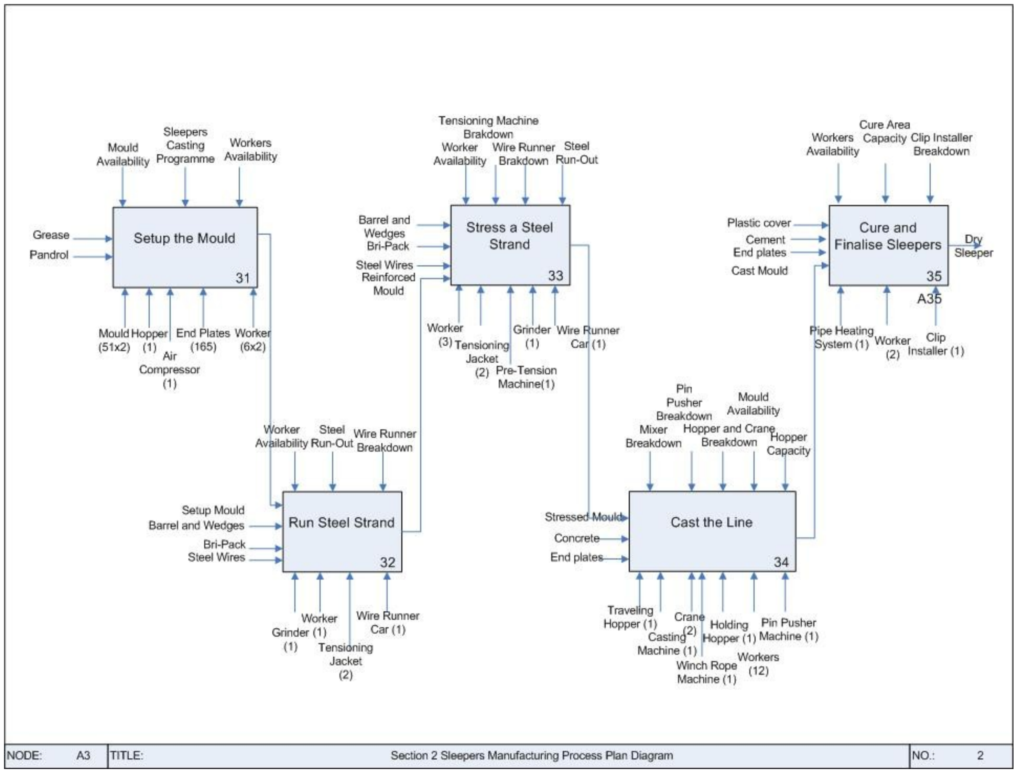


Figure H-3: process mapping diagram of precast concrete manufacturing system of company C

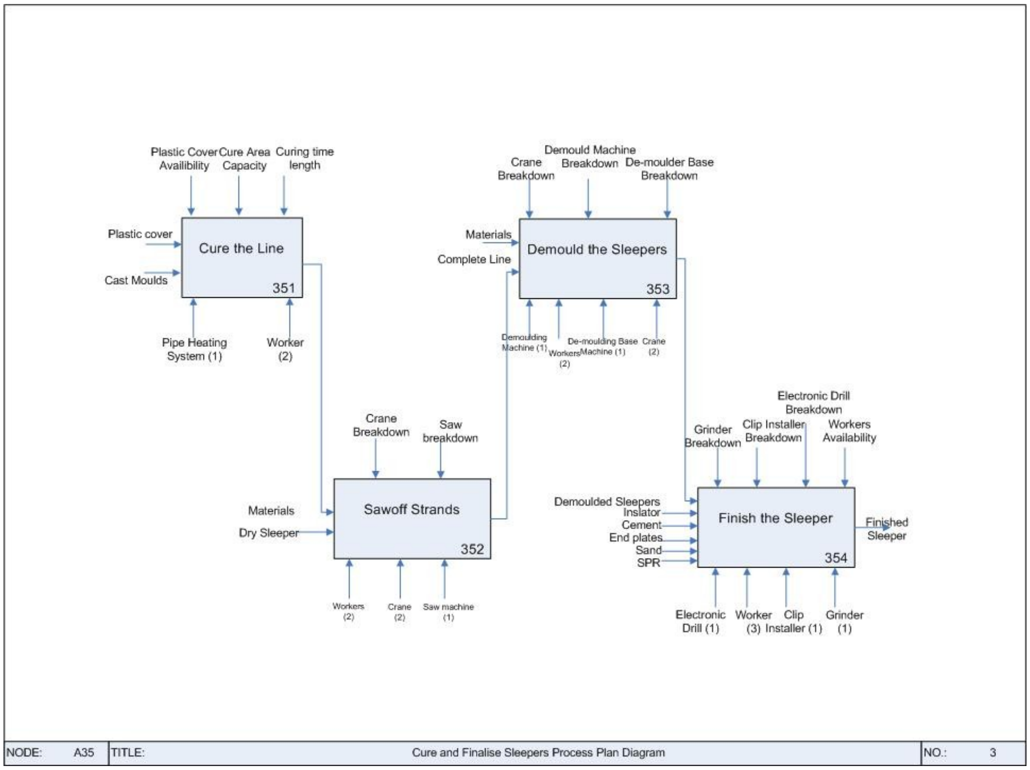


Figure H-3.1: process mapping diagram of precast concrete manufacturing system of company C (Cont)

Appendix I: Logic of Production Processes (Section 1)

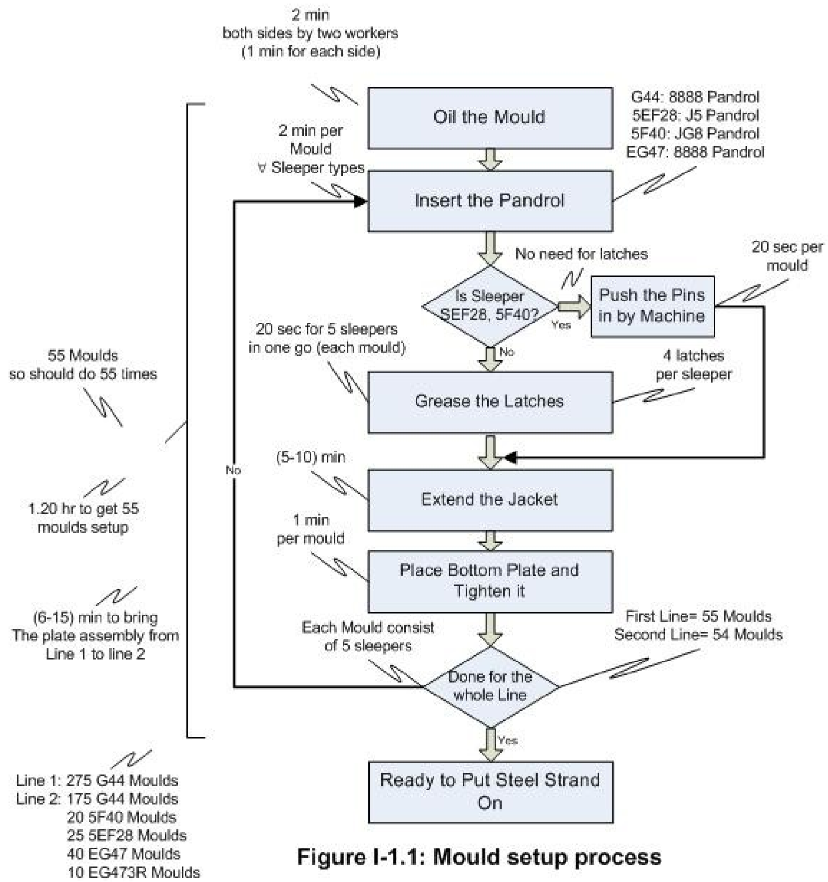


Figure I-1.1: Mould setup process

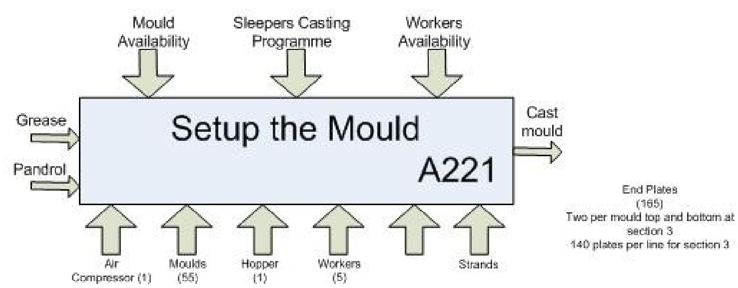


Figure I-1.2: Mould setup process

Picture I-1.1: Gang mould with pandrol in

Picture I-1.2: Gang mould to put steel strand on

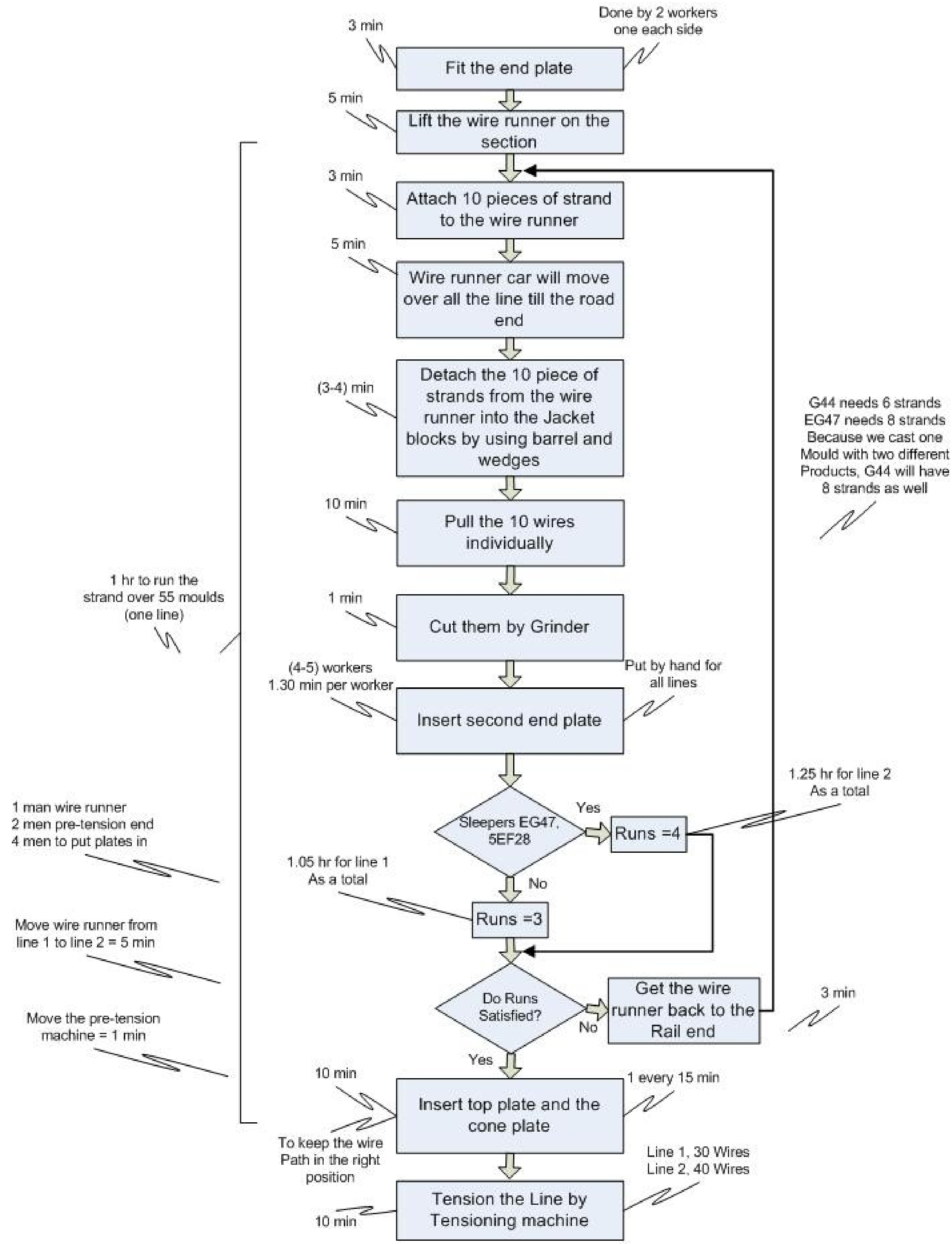


Figure I-2.1: Placement of Steel Strand Process

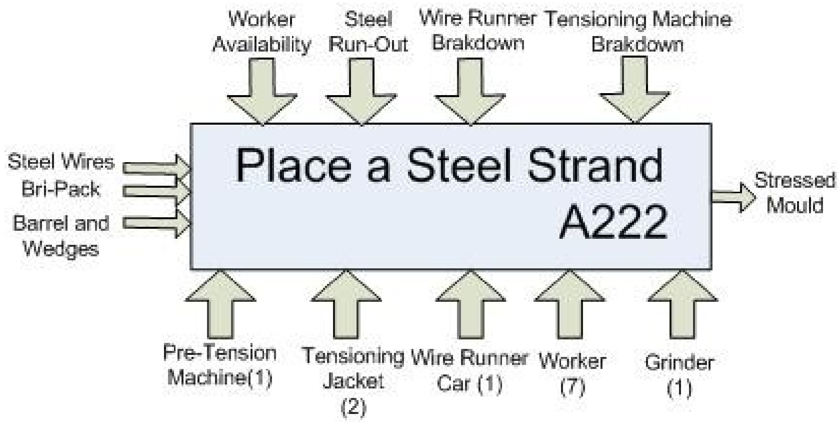


Figure I-2.2: Placement of Steel Strand Process

Picture I-2.1: Tensioning Jackets

Picture I-2.2: Double tensioning Jackets

Picture I-2.3: Wire runner car

Picture I-2.4: Pre-tensioning machine

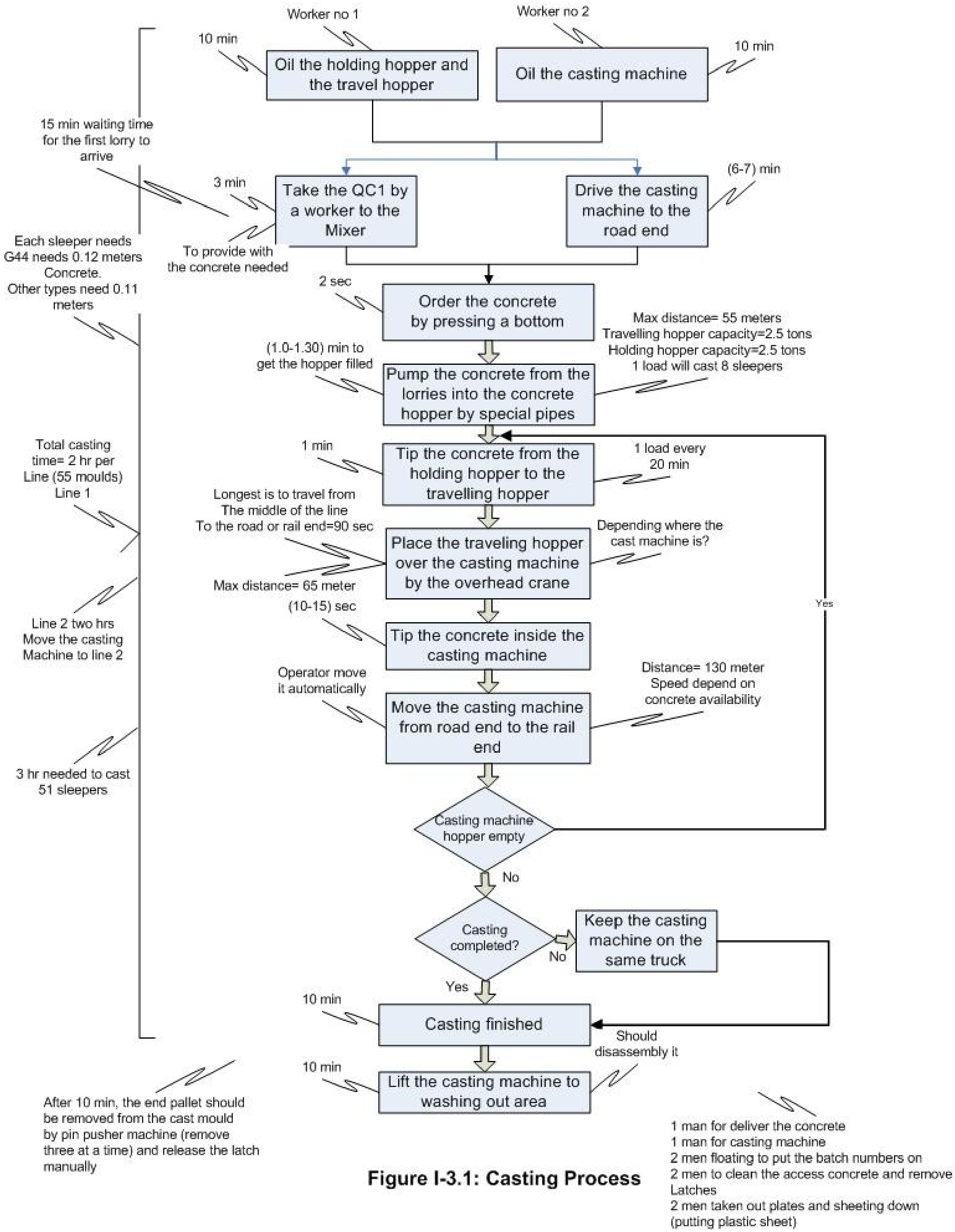


Figure I-3.1: Casting Process

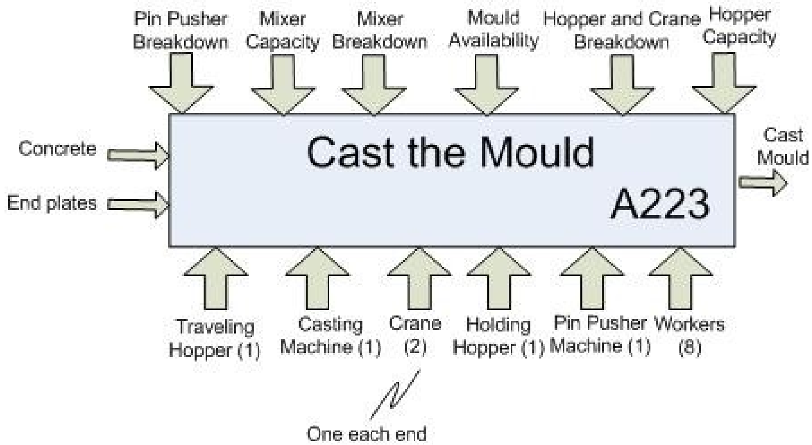


Figure I-3.2: Casting Process

Picture I-3.1: Traveling hopper

Picture I-3.2: Holding Hopper

Picture I-3.3: Casting machine

Picture I-3.4: Cast mould

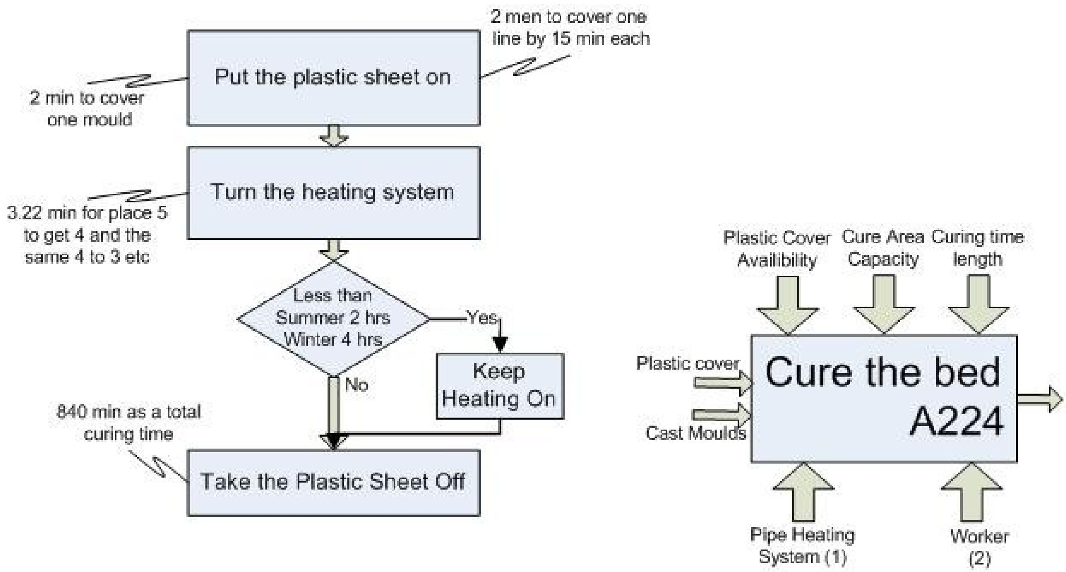


Figure I-4: Curing Process

Picture I-4.1: Cure mould

Picture I-4.2: Gang mould with plastic sheet on

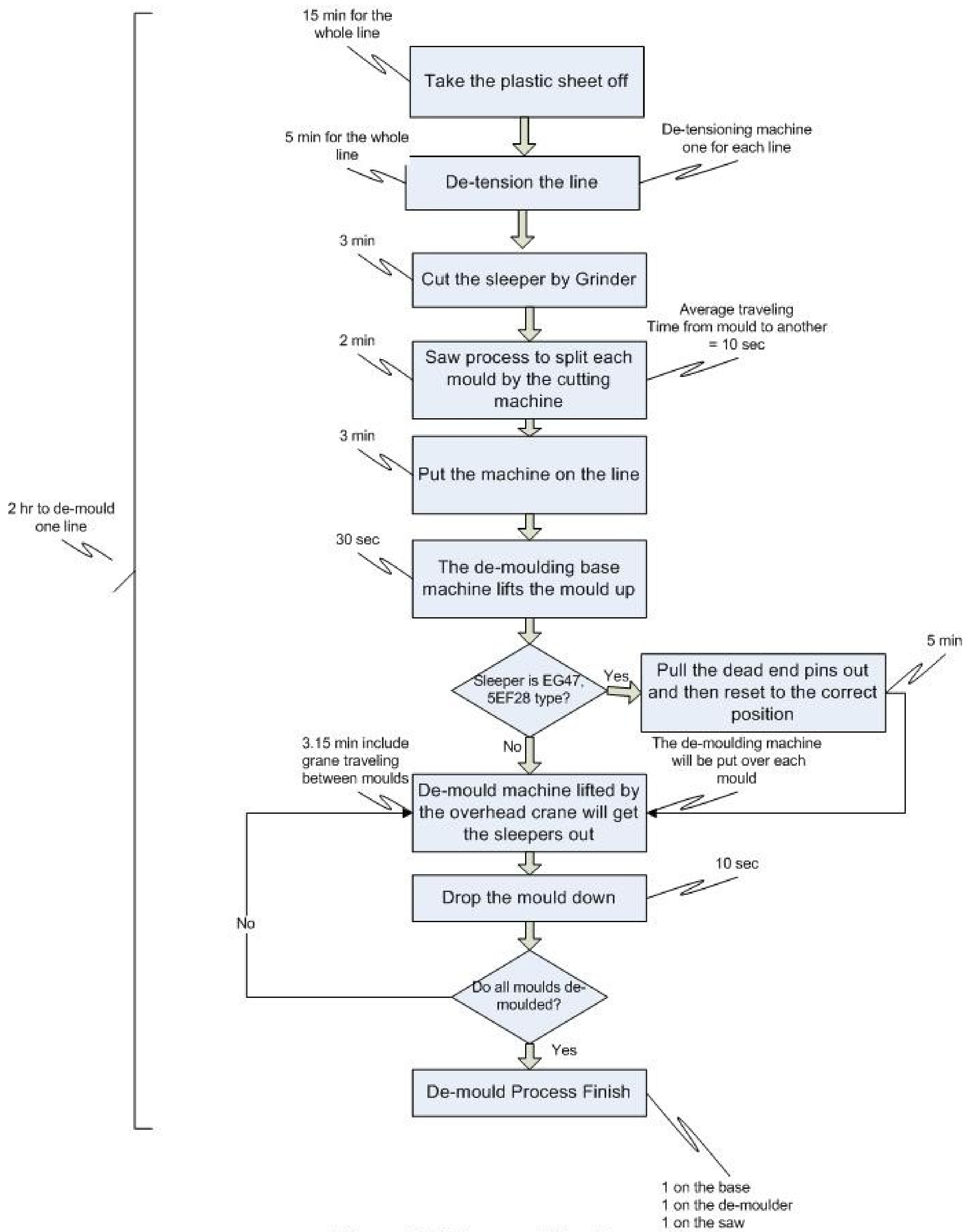


Figure I-5.1 De-moulding Process

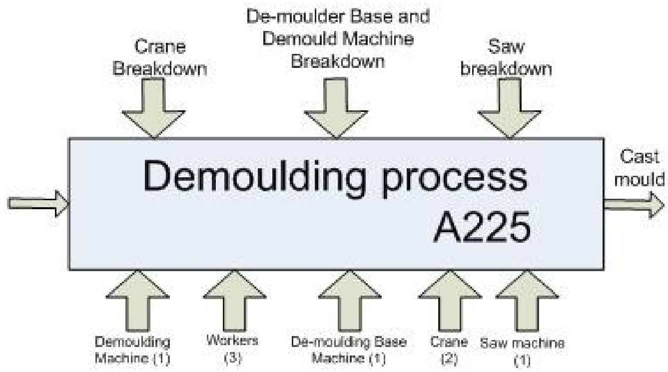


Figure I-5.2: Finishing Process

Picture I-5.1: Demoulding-base machine

Picture I-5.2: Demoulding machine

Picture I-5.3: Crane lifts the demoulding machine

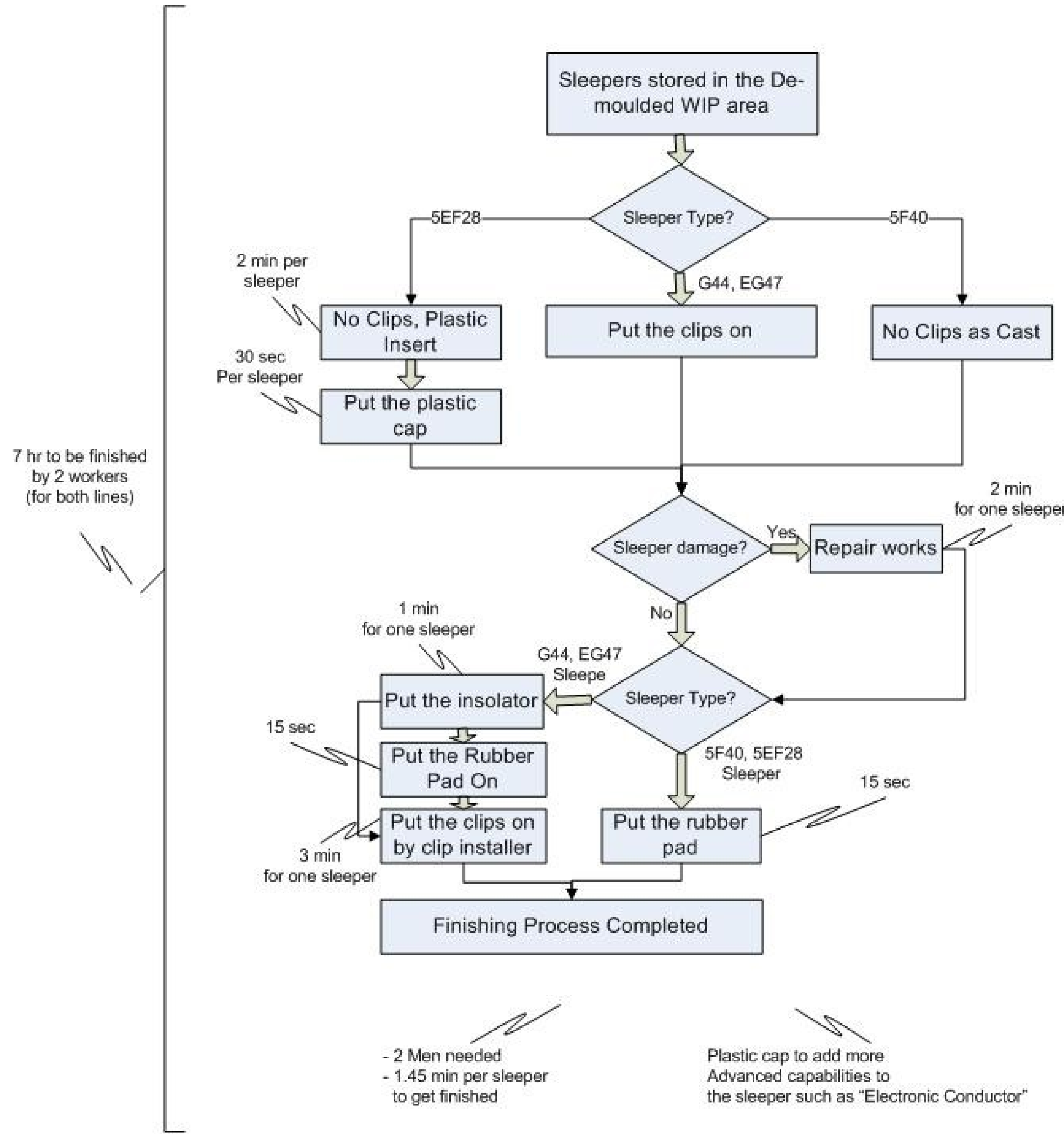


Figure I-6.1: Finishing Process

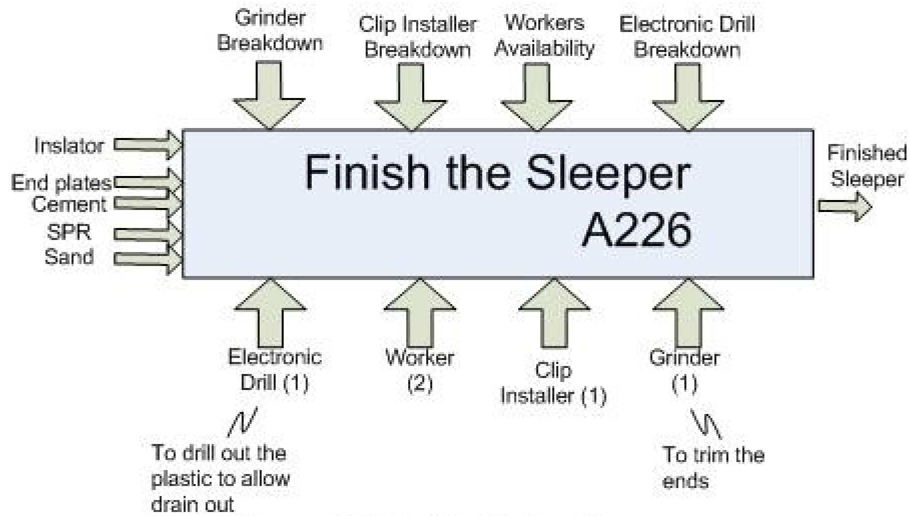
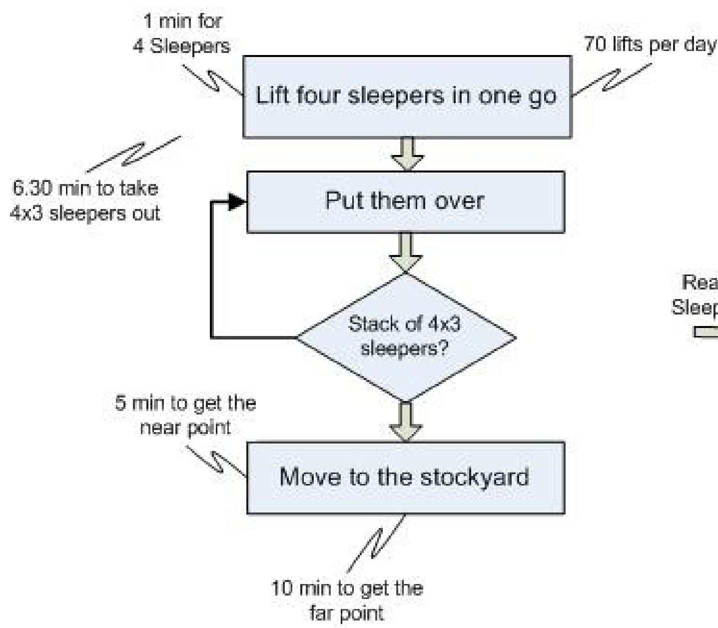


Figure I-6.2: Finishing Process

Picture I-6.1: Sleepers in WIP area

Picture I-6.2: Repair works



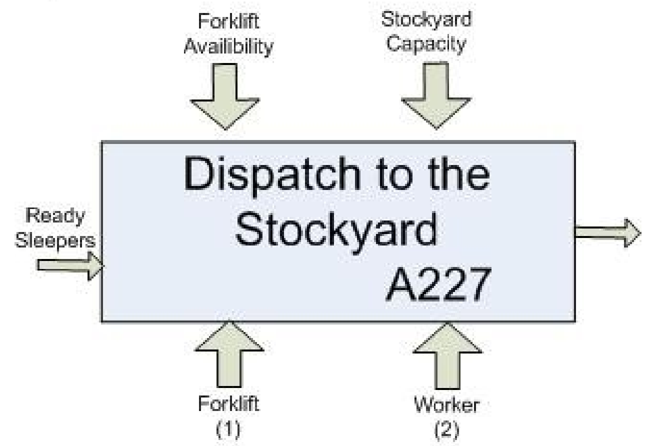


Figure I-7: Dispatching Process

Picture I-7.1: Forklift lifting sleepers

Picture I-7.2: Dispatch sleepers

Appendix J: Logic of Production Processes (Section 2)

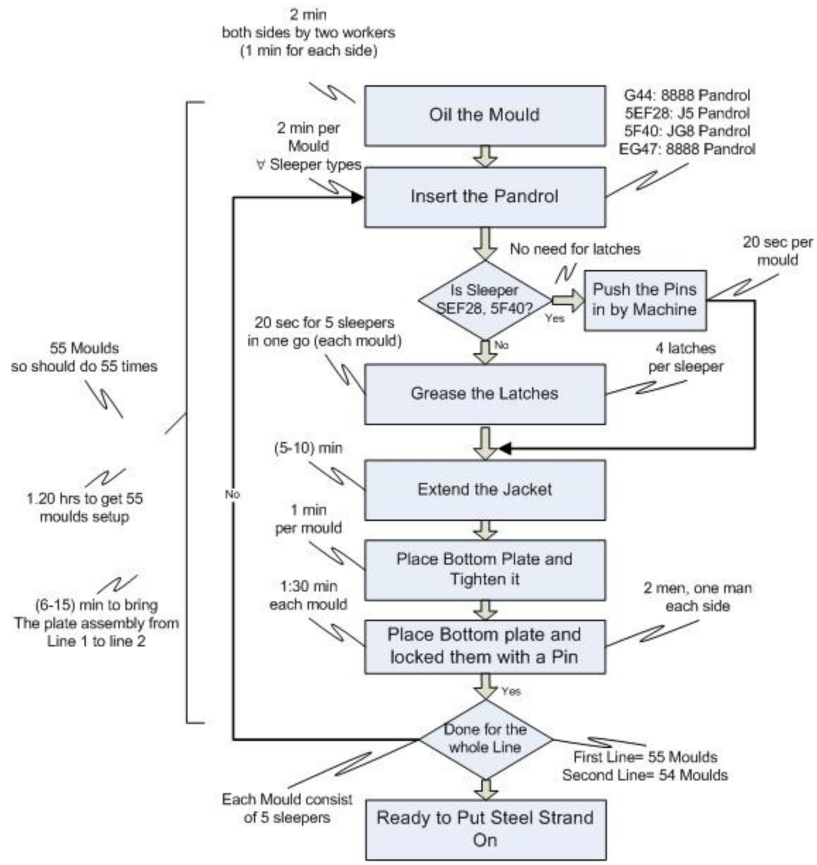


Figure J-1.1: represent setup the mould process

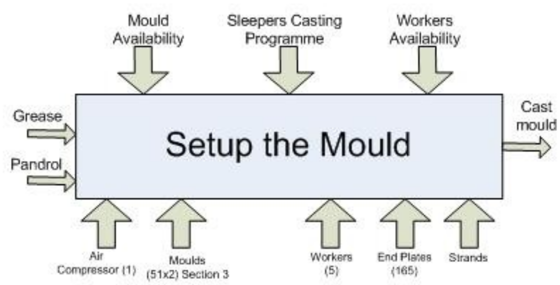
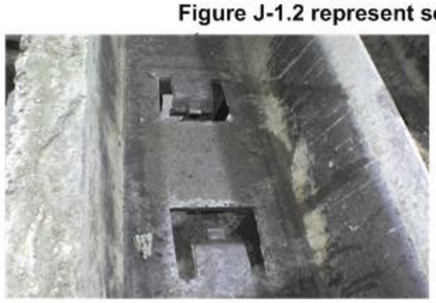


Figure J-1.2 represent setup the mould process



Picture J-1.1: Mould without pandrol

Picture J-1.2: Gang mould without pandrols

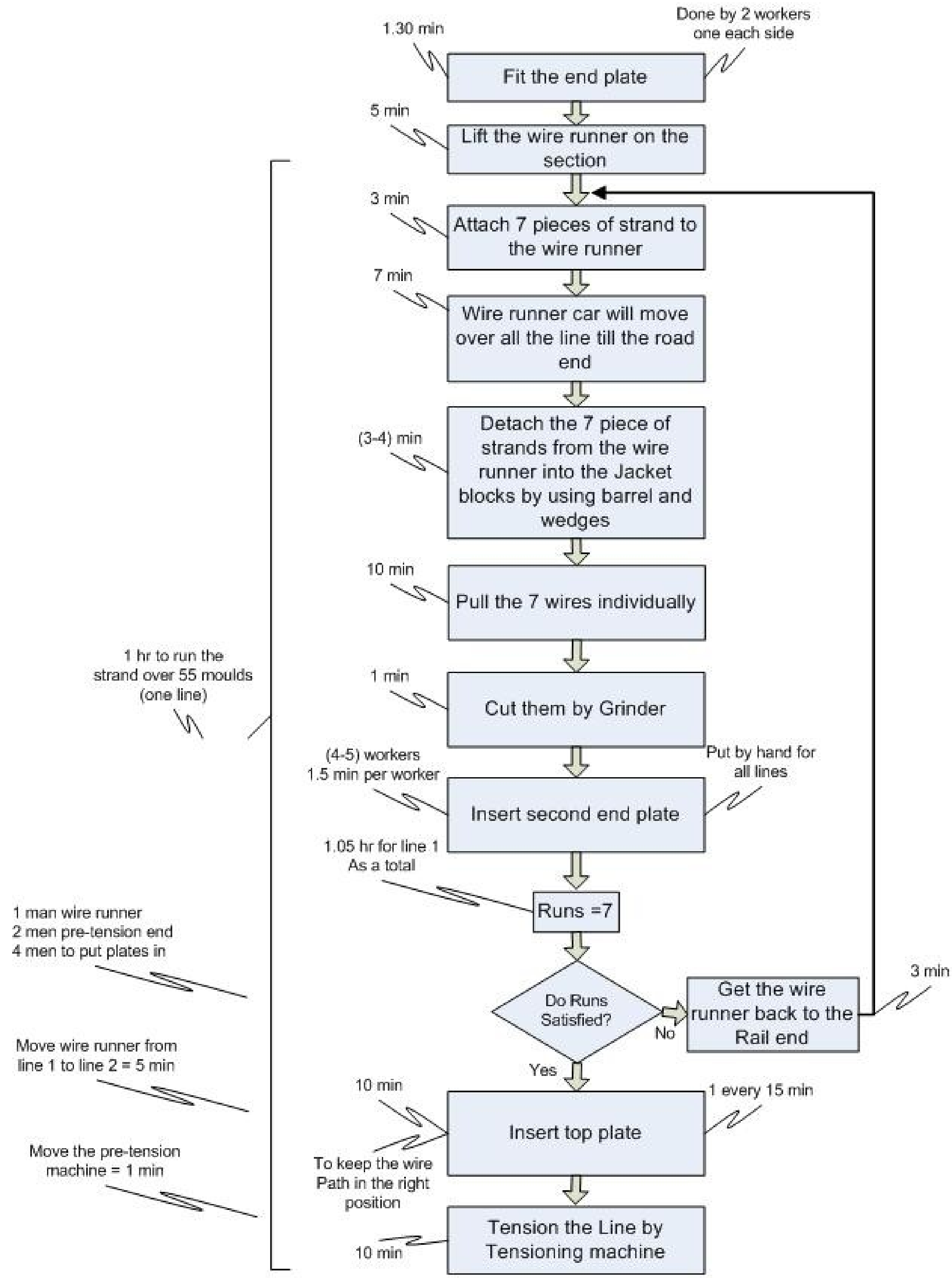


Figure J-2.1: represent the placement of steel strand process

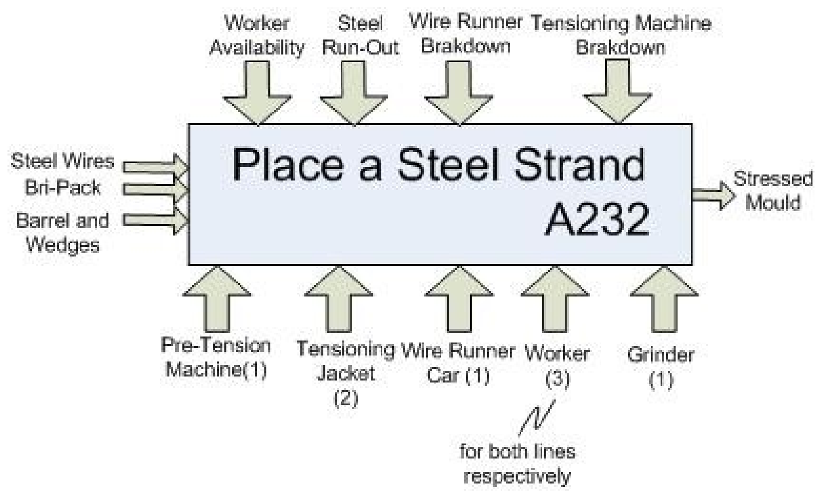


Figure J-2.2: represent the placement of steel strand process

Picture J-2.1: wire runner car

Picture J-2.2: Tensioning jacket

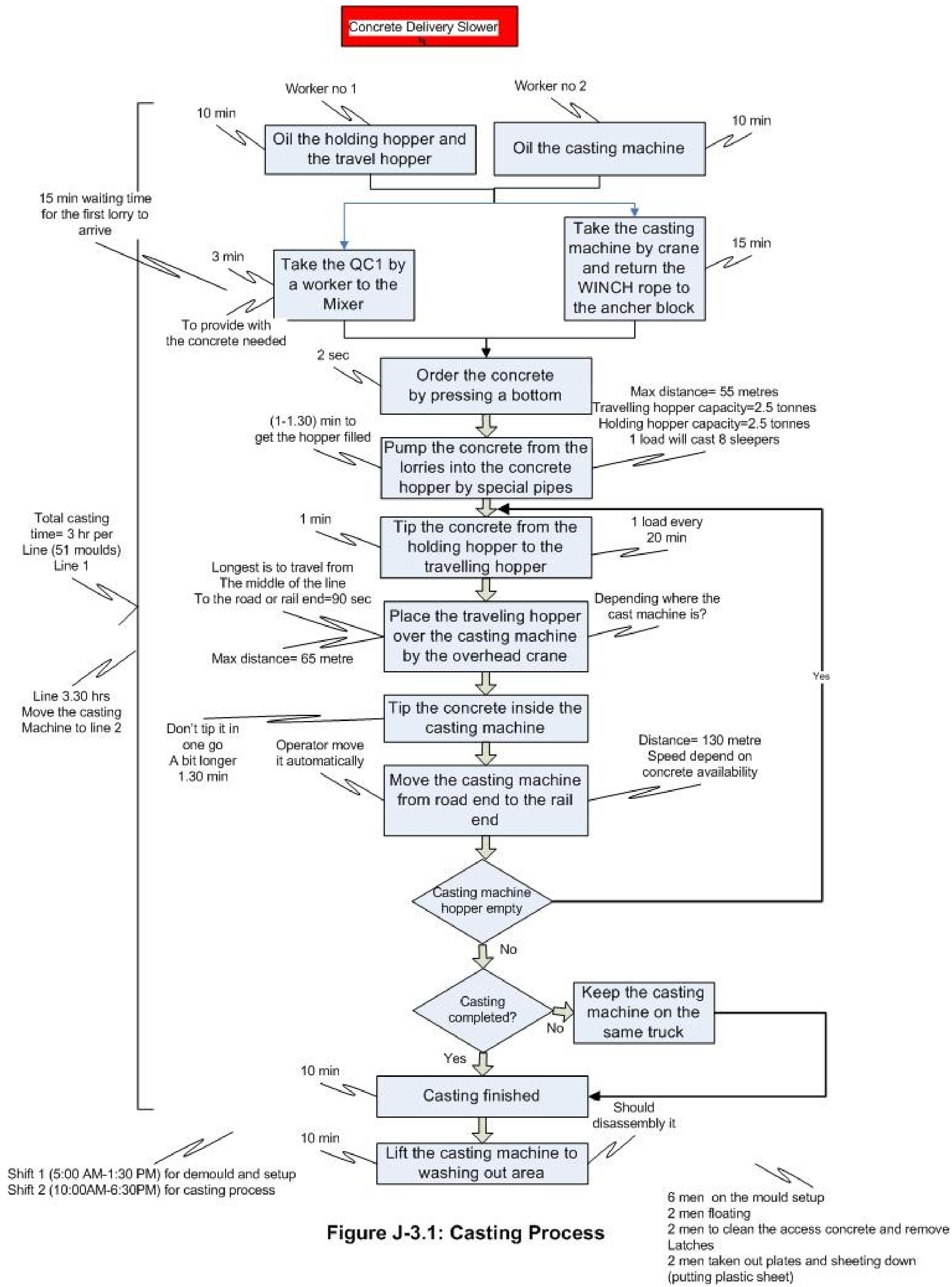


Figure J-3.1: Casting Process

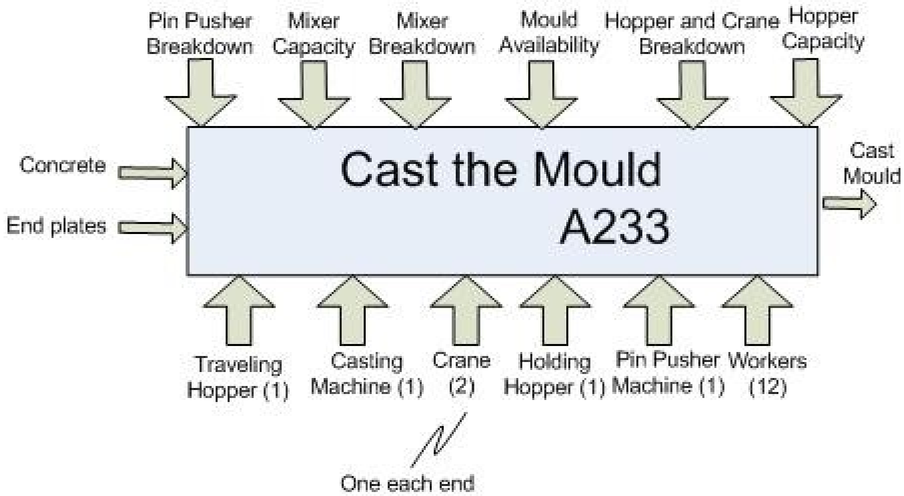


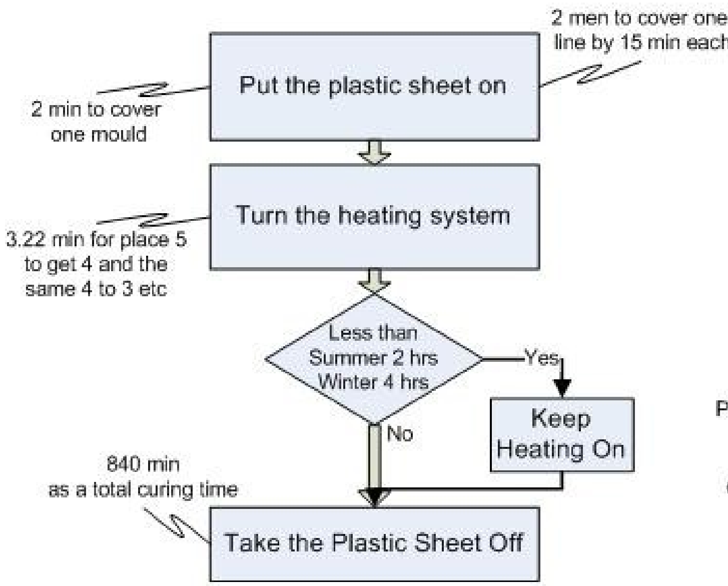
Figure J-3.2: Casting Process

Picture J-3.1: traveling hopper

Picture J-3.2: casting machine

Picture J-3.3: traveling hopper lifted by a crane

Picture J-3.4: holding hopper



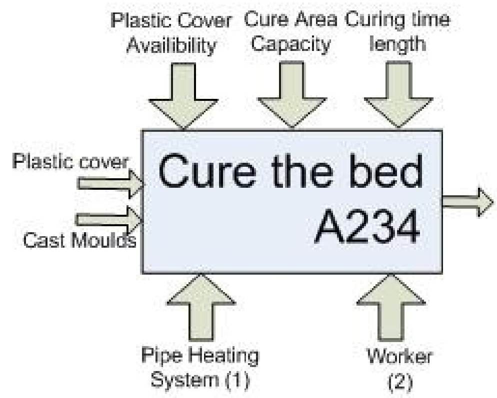


Figure J-4 Curing Process

Picture J-4.1: Partial casting to be cure

Picture J-4.2: gang mould being cured

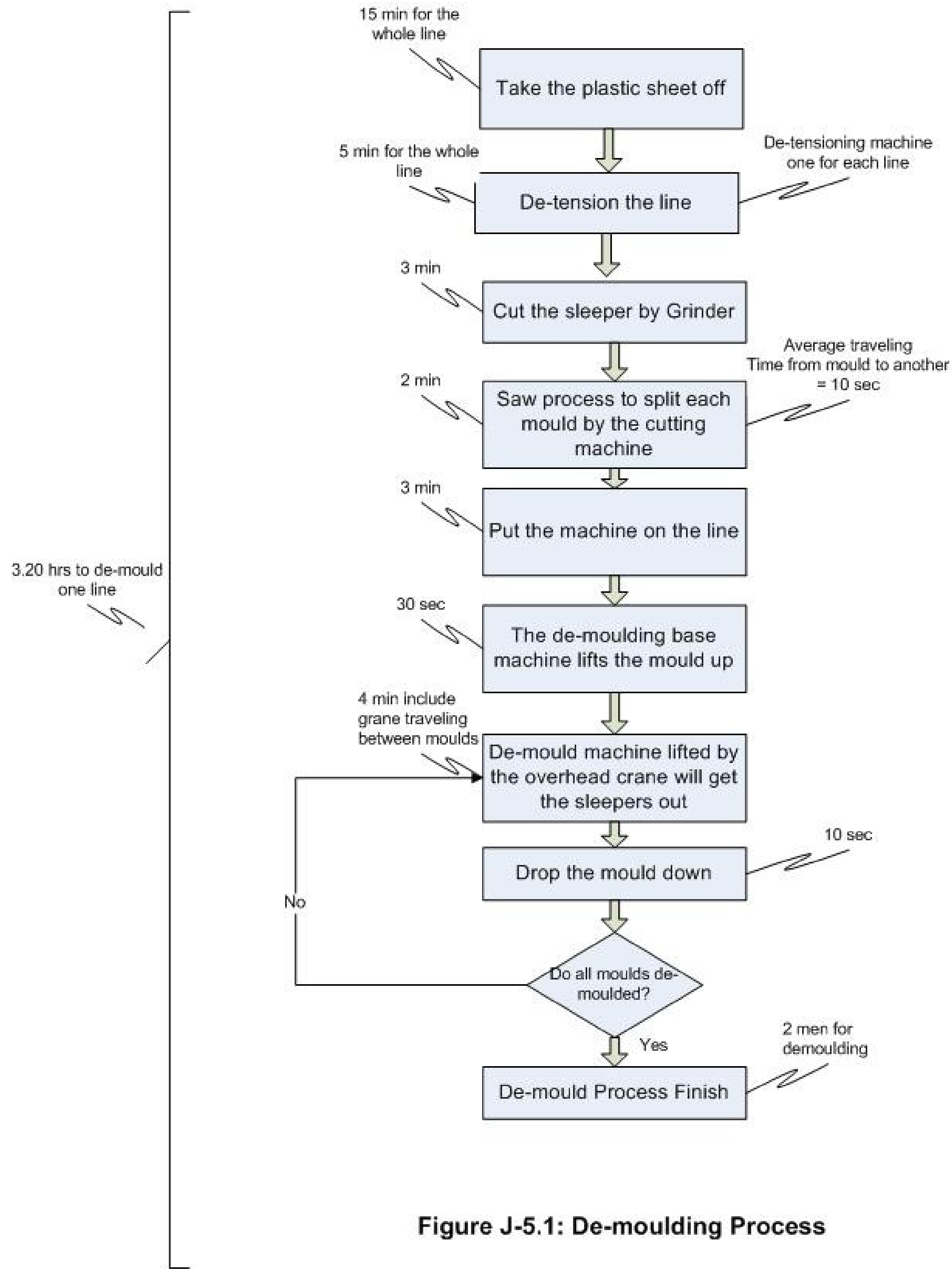


Figure J-5.1: De-moulding Process

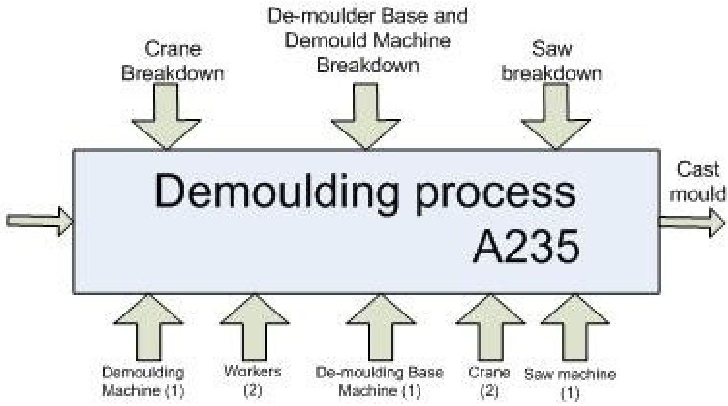


Figure J-5.2: De-moulding Process

Picture J-5.1: Demoulding machine

Picture J-5.2: Demoulding-base machine

Picture J-5.3: Demoulded Sleepers

Picture J-5.4: Crane lifts demoulder-base

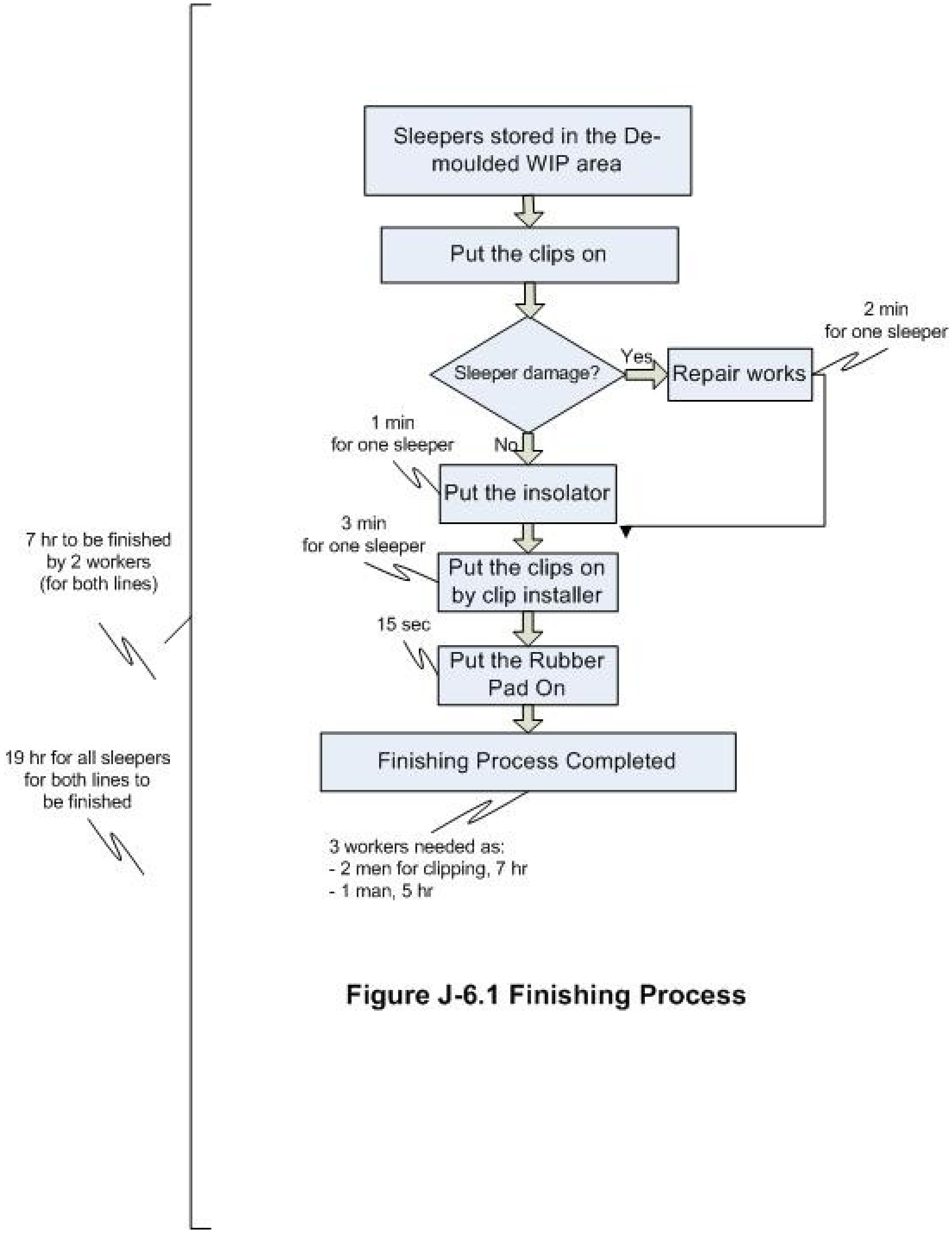


Figure J-6.1 Finishing Process

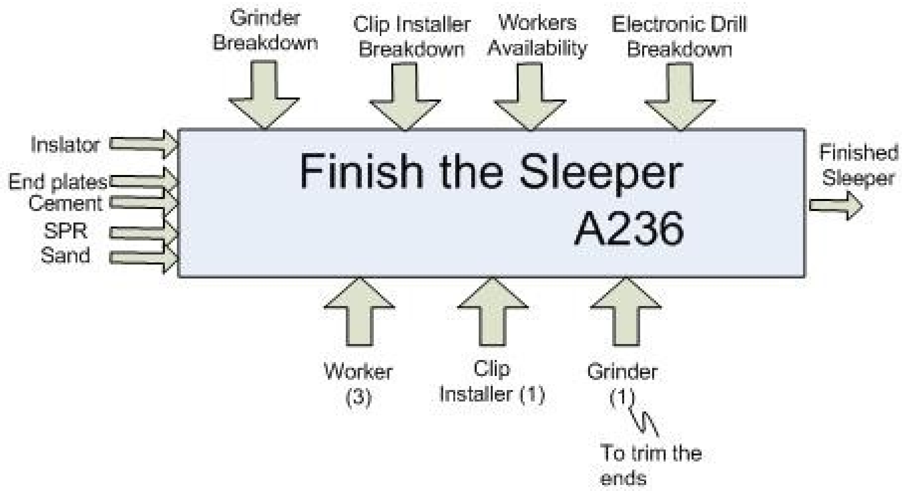


Figure J-6.2 Finishing Process

Picture J-6.1: repair work

Picture J-6.2: clip installing

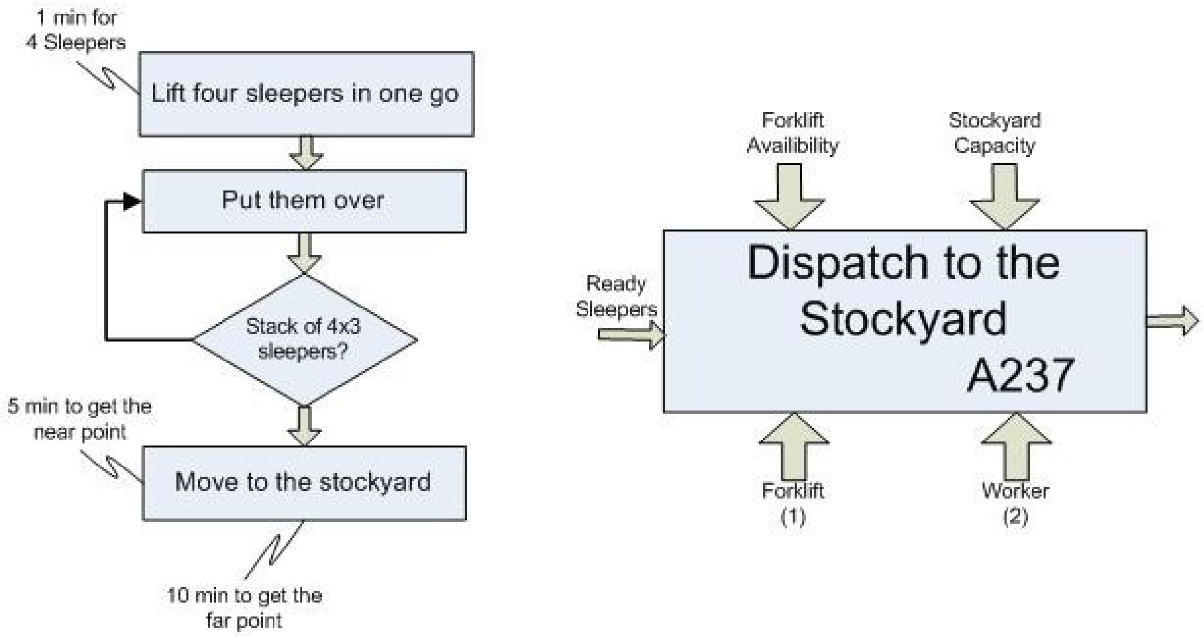


Figure J-7 Dispatch Process

Picture J-7.1: Trailer shipping sleepers

Picture J-7.2: Sleepers upload by a forklift

Appendix K: Structured Interviews Feedback

Internal Questions: Problem Identification

Interview Question	Response Summary	Actions Taken
1. Which precast concrete business section can affect on increasing production cost?	• *The manufacturing site is the main source of production cost.* • *The direct cost which includes labour allocation and other allocation costs is the main source of production cost.*	• *Inspect company's business sections.* • *Develop a high level business process map.*
2. What was the main reason of having high production cost? Was it due to resource allocation?	• *Resource allocation is the main source of high cost.* • *Usage of physical resources (machine, mould, cranes) alongside the utilisation of highly skilled workers is the key component of operating cost. .* • *Inappropriate use of skilled workers adds significantly to production cost.*	• *Conduct further analysis to identify the causes of such increasing.* • *Visiting the financial department to identify the causes of increasing production costs.*

Appendix K: Structured Interviews Feedback

Internal Questions: Problem Identification

Interview Question	Response Summary	Actions Taken
3. What type of delay occurred while sharing resources and how can this affect on system performance?	• *Process-waiting time can occur while sharing resources in more than one production line.* • *Waiting time results when any process waits for a resource or collection of resources to carry out any activity using this process.* • *Waiting time can affect the performance of production system as a result of longer production times and lower utilisation rates.*	*Inspect two production lines to check the delay which can be occurs while sharing de-moulding resource.*
4. Does the current worker allocation plan work?	• *Any allocation plan can work, but there is concern that no optimisation process exists.* • *There is a key required to reduce cost by improved labour utilisation.*	*Investigate and identify other possible alternative allocation plans.*

Appendix K: Structured Interviews Feedback

Internal Questions: Problem Identification

Interview Question	Response Summary	Actions Taken
5. Is sharing of resources within parallel layout of repetitive processes affecting production performance?	• *Yes, the resource sharing problem can significantly affect performance.* • *Resource sharing should be synchronised in such a way that minimum process-waiting time can be obtained.* • *Workers should be assigned to be ready to start job processing at the required time within the process.*	*Develop a schematic diagram of the manufacturing system layout.*
6. Did resource sharing slow the production process?	• *Yes, resource sharing results a process-waiting time which can affect on the flow of production process.* • *Such waiting time can be considered as an additional disturbance to the flow of the manufacturing system.*	*Pay more focus on shared workers and their skills in processing jobs.*

Appendix K: Structured Interviews Feedback

Internal Questions: Data Collection

Interview Question	Response Summary	Actions Taken
7. What are the production processes that are affected due to resource sharing?	*A part of the curing process and all other processes can be affected by the resource sharing issue.*	• *Inspect the curing process.* • *Address all processes that use shared resources.*
8. Which production processes are affected by mixer sharing? How?	• *Any delay in delivering concrete can slow the processing of a number of production processes especially those following casting processes.* • *Mixer sharing mainly affects the casting process of each production line.*	• *Model the mixer operation as the only provider of concrete.* • *Model all other processes to be totally dependent on one mixer.*

Appendix K: Structured Interviews Feedback

Internal Questions: Data Collection

Interview Question	Response Summary	Actions Taken
9. What are the influential factors that affect the production performance in each production section? What are shared resources used?	• *A number of influential factors can have an effect on the production processes at each production section.* • *Mixer capacity and resources availability can affect the production process.* • *A number of physical resources and workers can be used to carry out jobs at each production process.*	• *Develop process maps for manufacturing process in each production section to identify process limitations, inputs, outputs, and controls.* • *Develop a detailed flowchart to reflect the logic of each production process.*
10. What is the logic of each production process at each line?	• *Four production lines are available in two production onsite sections.* • *Each production line has eight production processes.* • *Processes are similar at each production line.* • *Shared resources worked in carrying out jobs on each production line.* • *Each process has a set of crew alternatives ready to be assigned on.*	• *Develop a detailed flowchart to reflect the logic of each production process.* • *Develop process map of the manufacturing site.*

Appendix K: Structured Interviews Feedback

Internal Questions: Data Collection

Interview Question	Response Summary	Actions Taken
11. What type of information required during the process of allocating crews?	*All labour information such as worker name, skills, hourly wage, crew formation, crew alternatives, shift workers and process names. In addition, all process logic has to be well defined in the system.*	*Develop a database in order to store and structure all the mentioned information.*
12. What are the outputs of the resource allocation process?	*Optimal allocation plan including time and related cost related. Crew formation utilisation is highly required beside the process-waiting time. The allocation plan in terms of printed tables is highly recommended to organise the allocation process of workers.*	*Define outputs of the conceptual model.*

Appendix K: Structured Interviews Feedback

Internal Questions: Improvement and Solutions

Interview Question	Response Summary	Actions Taken
13. Do you think minimisation of process-waiting time can improve the line efficiency?	• *Yes as better flow of work can be achieved when shorten process-waiting times.* • *The jobs then can easily be processes through a series of production processes without any disturbance.*	*Review of a number of related manufacturing studies in process-waiting time and possible effects on system performance.*
14. What do you think about developing a computerised crew allocation system to ease the allocation process of crews?	• *I think developing such computerised systems enable us to investigate a wider range of allocation scenarios as it save both time and cost.* • *The other point of view is that using of such system would be difficult to be used by us.*	• *Conduct a comprehensive literature review in order to identify the state-of-the art of allocation systems.* • *Develop a conceptual model of the allocation system.*

Appendix L: Industry Feedback about 'SIM_Crew'

In order to figure out the reaction of industry about such allocation system, the developed model was presented in the precast manufacturing company to the production planner and a number of workers with different skill levels. The production planner and the senior chargehand of production sections commented on the developed system saying: "*it is hard for us to use such advanced systems since lots of academic background and modelling skills are needed to be understood before using it*".

In addition, the production planner added "*we have no knowledge about how to maintain such complex system, i.e simulate any changes in the real system or change some of the simulation modules to be compatible with any real life changes*".

The senior planner addressed the shortcoming of this system to handle absent workers. His comments identified the limitation in such system in terms of rescheduling and submitting an instantaneous allocation plan when any absence case occurs.

Appendix M: Comments and Suggestions to the Industry

The interface mechanism was developed to simplify the human interaction with the designed system. The processes and workers information were designed to be obtained easily through the developed Access database. The system was been simplified in a way that any person familiar in using Access database can interact and run it.

A suggestion was made to run a short training course about how to use the allocation system. The main focus of this course is on how to add/remove process, crew, worker, etc. The production planner would be selected to undertake this sort of course and will be the only responsible for using the system. (crew formation of each process) being printed on a daily or weekly worksheet to be seen and used by the worker force. A consultancy service can be offered regarding the maintenance of the simulation model and increasing it capabilities further.

The prediction of workers absence situation was not considered when designing such allocation system. This system can be developed more to be able to handle such stochastic situations.

Appendix N: Benefits of the Proposed Crew Allocation System in the Precast Industry

The main benefits of the 'SIM_Crew' crew allocation system are as follows:

- Improves the performance of the production processes – labour intensive process and subsequently the reliability of the precast manufacturing system.
- Ensures that the right crew is available at the right time and at the right place.
- Reduces the cycle time and overheads of crew planning.
- Prevents schedules from conflicting with different kinds of constraints and that they comply with laws and regulations appertaining in the processes studied.
- Optimisation of the utilisation of labourers and minimisation of both process-waiting time and labour allocation cost.
- Quantifies the impact of adopting different crew allocation plans on the precast concrete products manufacturing system being investigated.
- Identifies and analyses improvement opportunities.